AN INVESTIGATION OF ELECTROMAGNETIC INTERFERENCE CAUSED BY DIFFERENT TYPES OF CORONAS IN AIR

by

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R. K. SRIVASTAVA

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TO MY

WIFE

CERTIFICATE

This work entitled 'AN INVESTIGATION OF ELECTROMAGNETIC INTERFERENCE CAUSED BY DIFFERENT TYPES OF CORONAS IN AIR' by R. K. Srivastava has been carried out under our supervision and this thesis has not been submitted elsewhere for a degree.

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ABSTRACT

Corona or stable partial discharge in free air occur in the power system under extremely nonuniform field condition. Three types of corona can be distinguished according to their occurrence under given electrode conditions. These are known as Glow, Streamer and Leader corona. Whereas glow and streamer coronas are allowed to take place at free electrodes, the leader corona takes place only in the form of surface discharge or tracking in the power system. Generation of all three types of corona leads to electromagnetic interference (EMI) to communication systems.

In this work a detailed description of the types of fields, coronas and the conditions under which they may occur is described. Experimental investigations have been performed to analyse the extent of EMI caused by three types of coronas separately. EMI measurements have been made with the help of a spectrum analyzer using Biconical and Spiral Log Cone type antennae designed for 25 to 200 MHz and 200 to 1000 MHz respectively. Suitability of spectrum analyzer for this kind of investigation has been well established. Interference on the actual TV screen have also been recorded.

EMI due to *glow* and *streamer* corona were predominant upto 460 MHz and 160 MHz respectively. Leader corona, which could be produced in our laboratory in the form of surface discharge or tracking, can cause interference up to 1000 MHz. As regard the field intensity of EMI measured in terms of spectral intensity dBμV/ m MHz was measured to be maximum due to leader corona.

CONTENTS

CHAPTER 1

INTRODUCTION

It is well known that the electromagnetic waves are produced due to corona generated by ac power frequency which cause interference to communication systems like telecommunication lines [1], radio transmission [2,3] and distortion in pictures of television receiver [4]. It also interferes with personal computers, video cameras and word processor etc [5]. Transmission lines, substations, including convertor & invertor stations, are the main source of corona in the power system [6]. A new approach to distinguish among the types of coronas has categorized them into three main types. These three types of coronas are known as glow, streamer and leader corona. In this work the extent of electromagnetic interference to communication system caused by individual types of coronas has been investigated.

In search of suitable equipment for the measurement of electromagnetic interference (EMI) due to corona, spectrum analyzer [7,8] was used and found to be most appropriate. The earlier measurements have shown that the spectrum analyzer is an accurate , time saving and valuable instrument for the assessment of radio noise originated by coronas. For instance measured data can be recorded quickly over a wide range of frequency compared to long time required for the manual measurements. Better resolution and more accurate information can be obtained with the help of this instrument . When short duration EMI changes occur, the instrument is found to respond instantaneously. Experience during such measurements revealed that the instrument could show the distinction between the radio signals and EMI clearly.

Starting with the types of electric field and coronas, description of test setup, the extent of EMI caused by different types of coronas and the measurement of impulse bandwidth have been discussed in this report.

CHAPTER 2

ELECTRIC FIELDS AND CORONAS

In this chapter various types of electric fields and types of coronas and the conditions under which they may occur are described. Factors which affect intensity of corona and their effects in atmospheric air are also discussed.

2.1 CLASSIFICATION OF ELECTRIC FIELD :

The electric field configuration are classified under following headings:

i) Uniform field

ii) Weakly nonuniform field

iii) Extremely nonuniform field

2.1.1 Uniform field :

In an 'uniform field' the potential is uniformly distributed and the electric field intensity is constant throughout the space between the two electrodes. Table 2-1 shows electrodes which generate uniform field. An important characteristic of this type of field is that insulation breakdown takes place without any partial discharge (pre-discharge) preceding the breakdown.

2.1.2 Weakly Nonuniform field :

Like uniform field in this type of field also, no predischarge occur before the breakdown. Electrodes like concentric spheres and coaxial cylinders having a 'radial field' can be the typical examples of weakly nonuniform fields, if the concentric electrode dimensions are not having a too large difference. Table 2-1 shows electrodes which generate weakly non uniform field. Despite field being weakly nonuniform, it is clubbed with uniform field since partial discharge inception voltage and breakdown voltages are equal for both these configurations.

2.1.3 Extremely Nonuniform Field:

There is an extremely nonuniform distribution of potential in the space between two needle electrodes leading to the nonuniformity of the electric field intensity. Table 2-1 shows electrodes which generate extremely non uniform field. This is typical case of an 'extremely nonuniform field'. Unlike in uniform field and weakly nonuniform fields, the insulation breakdown in extremely nonuniform fields takes place after stable predischarges are set. The predischarges are unstable only just before the breakdown. This field configuration is of great technical importance as it is the most unfavorable but common condition of electric field faced by a dielectric. At the tip of electrodes the dielectric is at a very high electric stress but elsewhere between the electrodes, it is stressed moderately. In this thesis corona, which occur only in extremely non-uniform fields are investigated to assess EMI caused by them.

Degree of uniformity (η) of any electric field is defined as the ratio of 'average electric field' to 'maximum electric field'. In air η equal to '1' is defined as uniform field, η greater than or equal to '0.2' is termed as weakly nonuniform

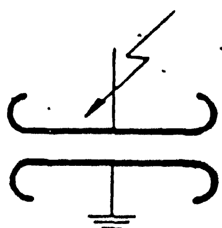
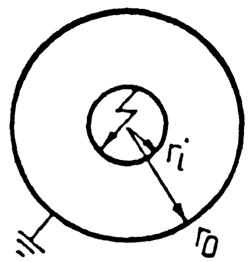
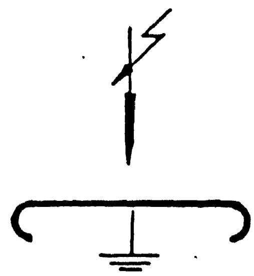
Field classification	Uniform	Weakly non-uniform	Extremely non-uniform
Electrode Configuration	Parallel plates 	Concentric spheres  r_i=0.25r_o	Needle-plane 
η	1	$0.2 \le \eta < 1$	$\eta < 0.2$

Table 2.1 : Shows electrodes which generate three types of electric fields.

field, and η less than '0.2' is defined as extremely non uniform field.

$$\eta = E_{av} / E_{max}$$

Where E_{av} and E_{max} are the average and maximum electric field intensity between two given electrodes respectively.

2.2 Types of corona :

Three types of corona discharges in gaseous dielectric are distinguished. These are following:

2.2.1 Glow corona

Because of steep fall in the field intensity (potential gradient) at very sharp points, edges or thin electrodes, the impact ionization which occur above a certain magnitude of field intensity, restricts themselves to very near the tip of the electrode.The avalanche formation is not able to acquire its critical amplification. The optical impression of such a partial discharge process is a weak bluish 'Glow', seen adjacent to the electrode. The electrons at high energy levels emit quantum of light and fall back to the original state of lower energy level. A hizz sound is produced at an increased intensity of *glow* discharge i.e. at higher voltages.

2.2.2 Streamer corona:

If the field pattern is modified so that the fall of field intensity (potential gradient) at the electrode is not so steep as above, partial discharges are able to extend deeper into the gap between the electrodes. This can be achieved between a sphere or hemispherical shaped rod and plane electrodes. The depth of region, where impact ionization is possible, is increased considerably giving rise to avalanche formation of above critical amplification. A different partial discharge process known as *streamer* corona.

Continuous development of a shower like discharge in a number of '*streamer* trajectories' spreads in the space around the hemispherical surface of the rod in the main field direction. The trajectories do not intersect each other. A number of weaker channels feed into the stronger channels which are comparatively less in number.

The word *streamer* also means a column of light shooting up in the '*Aurora*'. Compared to *glow*, a weakly illuminated bunch of discharge results due to the movement of pockets of ionized particles. The sound produced is a 'flutter', which may be heard before the *streamer* is seen.

The *streamer* discharge current is accompanied with an impulse form which may acquire its magnitude of a few milliamperes within nanoseconds.

2.2.3 Leader Corona:

If the same rod or sphere plane electrode system is provided with a long gap of the order of a metre and above, it will enable us to apply higher voltage at the anode without a breakdown taking place. Thus the *streamer* trajectories described above would be able to extend themselves more in the gap and develop stronger. The extended *streamer* phenomena thus produced is known as 'Leader

Discharge'. The discharge current density in some main trajectories increases so much that it results in thermal ionization.

The spatial propagation of the *leader* channel is of a narrow irregular path, often in a direction at an angle to the field. Hence it is also termed as stepped *leader*. The *leader* channels extend themselves due to injection of discharge current in these channel by the *streamer* corona at their tips. As the current density in the *leader* channel increase, it brings down the potential gradient required for its propagation.

As it was not possible to produce *leader* corona at a free electrode in air in the lab because of the limitation of the available test transformer, *leader corona* was produced in the form of tracking or surface discharge, occurring on the surface of a glass plate.

Some solid and liquid dielectrics have a property to track. Such discharges take place in the gaseous dielectrics on the top of solid or liquid dielectrics. Surface discharges consists of high conductivity channels giving rise to stable *leader* corona. Tracking discharges are commonly produced at substations where more of solid and liquid dielectrics are used.

2.3 EFFECTS OF PARTIAL DISCHARGE (CORONA) IN ATMOSPHERIC AIR:

In power system network i.e. HV transmission line & equipments, *glow* and streamer corona may occur at any unfavorable condition of free electrodes. However, the stable *leader* corona occur only in the form of tracking or surface discharge i.e.

either at bushing or some other solid insulators. Instable *leader discharge* also takes place wherever lightning occurs in the nature. The most common types of man made PD in air are *glow* and *streamer* coronas. It is very important to know the physical and chemical implications of PD in air or environment.

2.3.1 Audible Noise (AN):

Whenever one approaches a HV transmission line or passes by a substation, one may hear the audible (AN) noise produced by corona [9,10]. With the increase in transmission voltage levels to the order of 1200 kV, the problem of AN has become more significant. Severe restrictions are therefore imposed to keep a check on the level of audible noise [11].

2.3.2 Light:

Often in the darkness one may see visual corona discharges near HV transmission lines and substations.

2.3.3) Atmospheric Pollution:

If the intensity of corona is high, one may even smell the chemically decomposed gaseous products (Ozone generation) causing environmental pollution.

2.3.4 EMI:

The high frequency electromagnetic waves produced by corona, interfere with the overhead telecommunication lines, radio & TV receivers and are known as Radio interference (RI) and TV interference (TVI) or Electromagnetic interference (EMI), a more general term. Level of EMI near corona source is high and at a distance of 50 metre from source it is feeble.

2.3.5 Power Loss:

Corona is accompanied with power loss. The magnitude of power loss depends upon intensity of corona which may become rigorous under rain or snow condition.

2.4 FACTORS WHICH AFFECT THE INTENSITY OF CORONA:

2.4.1 Geometry of Electrode and gap distance:

The geometry of electrodes and gap distance determine the degree of uniformity of electric fields and hence the geometrical maximum field intensity on any electrode system at a given voltage.

2.4.2 Effects of Electrode Material and their Surface Roughness:

The quality of surface finish of a metal not only depends upon the metal itself but also upon the manufacturing and machining processes. The surface roughness may not be visible from naked eyes but it can be determined with the help of an electron microscope. An electrode with more roughness has low inception voltage in comparison to an electrode having fine finish of electrodes. Effect of material, if present, is because of its surface roughness and not because of material as such. However, material as well as the roughness have no effect on corona which takes place only in extremely nonuniform fields.

2.4.3 Effect of polarity:

The polarity of the voltage applied influences the space charge formations leading to the phenomenon of the field distortion which is responsible for the tremendous effect of the polarity on the intensity of corona. In case of ac power frequency voltage, the polarity is changing in periodic cycle giving rise to a mixed state.

2.4.4 Air Conductivity:

The conductivity of air varies greatly at different locations. In coastal areas conductivity of air is higher compared to the planes away from the coast. Even in hill region conductivity of air is high may be because of higher moisture content. This property of air may affect the PD.

2.4.5 Other atmospheric conditions:

Atmospheric conditions like dust, rain and snow affect the PD intensity too. Numerous rain drops when they hang from the conductor, give rise to severe corona of high intensity at uncountable number of points. Snow deposition on the conductor too increases the intensity of corona. These not only increase the power loss but also intensity of EMI tremendously.

CHAPTER 3

TEST SETUP

The experimental setup for the measurement of EMI is described in this chapter. The experiments were conducted in the HIGH VOLTAGE LABORATORY of The Department of Electrical Engineering, I.I.T.Kanpur. The whole set up is described in the following.

3.1 HIGH VOLTAGE SUPPLY:

The lab is equipped with a 100 k.V., 50 kVA, ac power frequency PD free test transformer.

A 1.1 nanofarad, 100 kV PD free high voltage condenser is used for the measurement of high voltage. The connection between above mentioned two equipments is achieved with the help of 5 cm dia, aluminium pipe, as shown in photograph (Fig. 3.1). Both the test transformer as well as the measuring condenser high voltage electrodes are provided a dome shape in order to prevent any partial discharge up to their rated voltage. A hollow spiral, steel pipe of about 2.5 cm dia is used to connect the dome with the test object. Care was taken to provide suitably shaped electrode at the end of this conduit pipe in order to suppress any PD.

For all PD measurements it is very important to ensure that the experimental setup is PD free and the partial discharges are produced only at the location desired. Our experimental setup in the lab was therefore first tested to prove itself to be PD free.

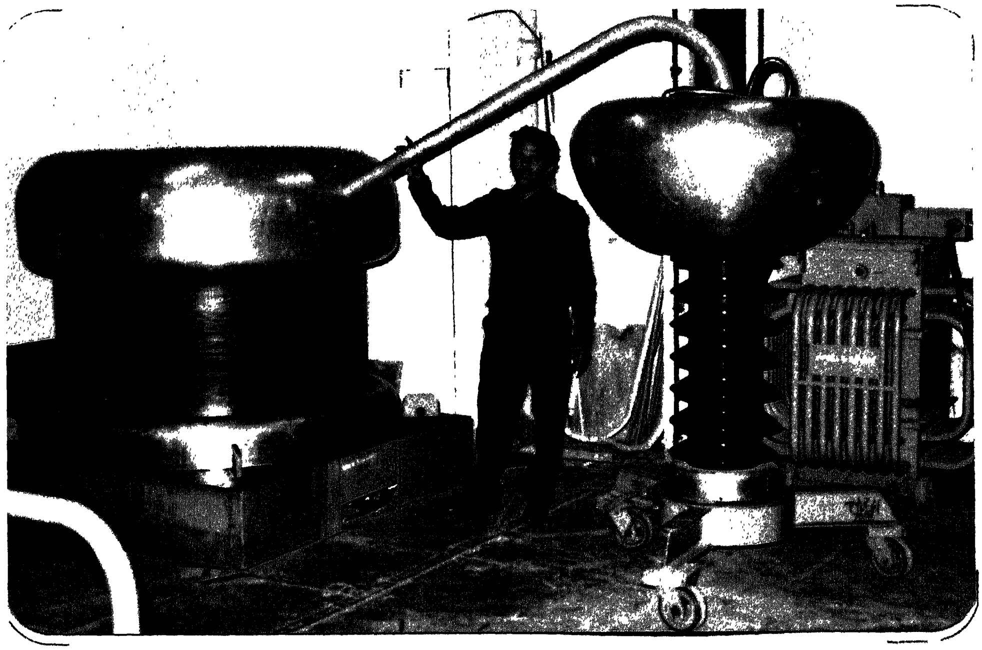


Fig. 3.1 : High voltage test transformer.

On making the measurements with spectrum analyzer it was found that the setup had partial discharge which incepted every time at 14 kV. In order to locate the PD, the circuit was disconnected and each equipment tested separately one by one. It revealed that the noise was produced from somewhere in the test transformer itself. At first a few very small sharp points and air gaps on the dome were suspected to have PD. The dome was removed. Still the same PD continued to appear and the inception of PD began at 7 kV itself. On checking the connections on the top of the transformer, where four lightening arresters were installed to protect the transformer from over voltages, it was revealed that a few short circuiting links, between the terminals coming out of the transformer through a number of bushings were missing. On making these links with the help of brass strips the PD noise was found not to be present. The whole setup was mounted again and tested to be PD free till upto 95 kV. It appears that due to missing links, high potential gradient across the bushings caused PD in the form of surface discharge which is nothing but leader corona.

3.2 SOURCE OF DIFFERENT TYPES OF CORONA:

Our aim in the laboratory was to produce three types of coronas namely *glow, streamer and leader corona.* Three experimental setups therefore were chosen to produce predominantly different kinds of coronas separately.

3.2.1 SETUP FOR GLOW CORONA:

Since it is known that the *glow corona* takes place at an extremely sharp electrode or point & edge, a 38 gauze fuse wire was taken as anode to produce *glow corona*. It was given a circular ring form of about 7 cm dia. A flat plate was used as cathode. Gap distance was taken about 20 cm. A brightly illuminated glow ring was visible to the naked eyes in the dark and a hizz sound was also produced. Figure 3.2 shows the setup for *glow corona*.

3.2.2 SETUP FOR STREAMER CORONA:

A hemispherical rod of dia 2.5 cm was used as anode to produce streamer corona. In order that no glow discharge takes place at the cathode it was given a suitable rounded shape. In this case also a gap distance of about 20 cm was used. The set up is shown in figure 3.2. At fairly high voltage of the order of 60 kV & above a less illuminated shower like discharge were seen at the rod. These discharges were accompanied with flutter sound.

3.2.3 SETUP FOR LEADER CORONA:

Since the laboratory has limitations with the source of power frequency voltage available only upto 100 kV, stable leader discharge (corona) was not possible to be produced on a free electrode in air. Hence a leader corona was produced in the form of surface discharge or tracking. The same electrode setup used to develop streamer corona was taken also to produce leader corona. An ordinary glass plate of 4 mm thickness was inserted between the rod and the plane electrodes. The rod resting on the glass and the glass resting on the plane, as shown in the figure 3.3. A plain glass is known to have the untidy property of

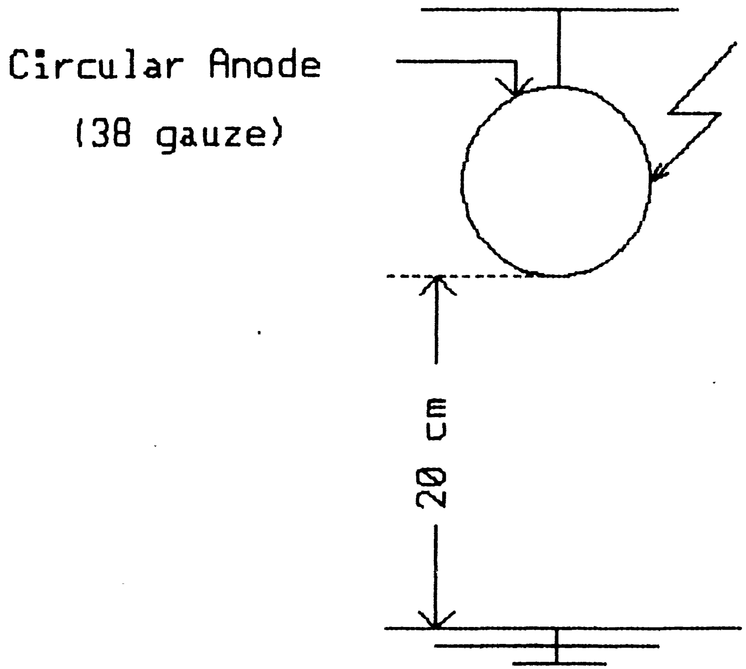


Fig.3.2: Setup for generation of glow corona

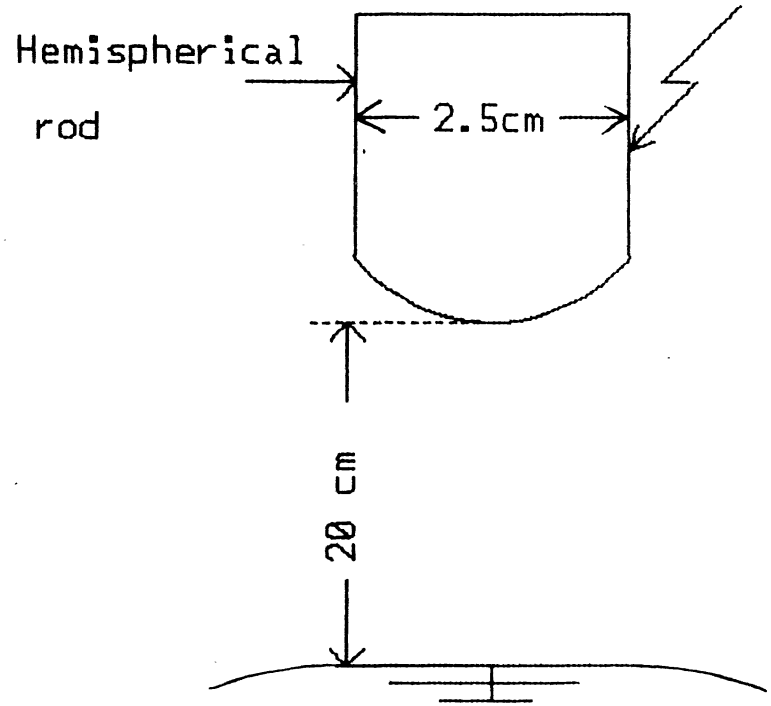


Fig. 3.3: Setup for generation of streamer corona

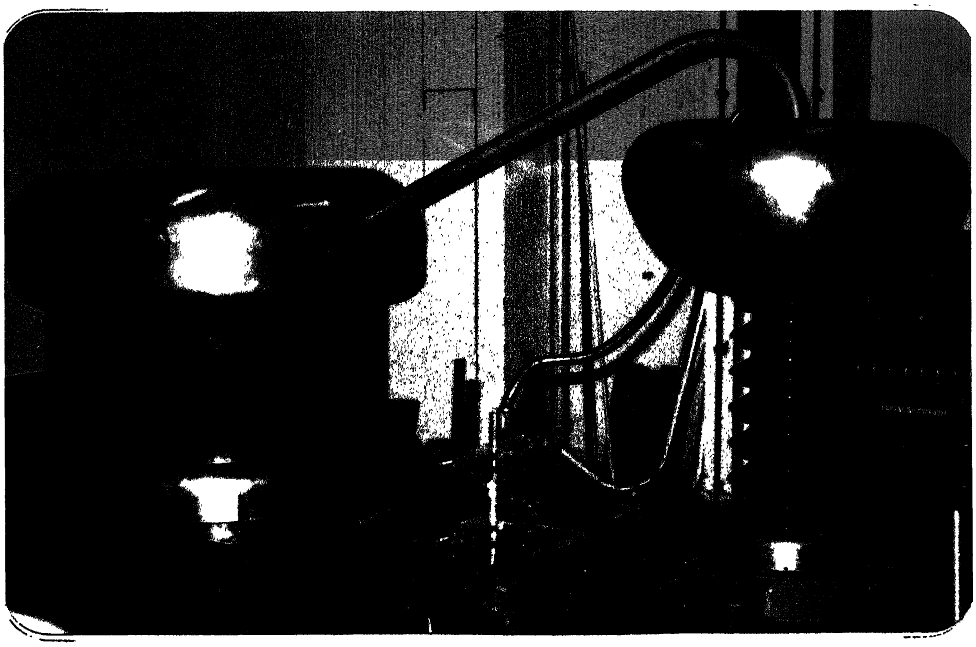


Fig. 3.4 : Set-up for generation of Leader corona

tracking. Vigorous tracking discharge in the form of brightly illuminated circular and radial leader channels were produced on this setup making cracking sound at fairly low voltage itself. In between the bright leader channels, lower intensity streamer discharges were also visible.

3.3 INSTRUMENTATION FOR MEASUREMENT OF EMI:

Evaluation of EMI was made with the help of a number measuring instruments, such as different antennae, amplifiers, spectrum analyzer, TV set and transistor radio.

3.3.1 SPECTRUM ANALYZER:

Anritsu MS 710F Spectrum Analyzer was used to measure the EMI level associated with observed corona discharges. This instrument is capable of covering a frequency range from 100 kHZ to 23 GHz. It is a swept front end type superhetrodyne spectrum analyzer. Figure 3.5 shows the schematic bloc diagram of spectrum analyzer.

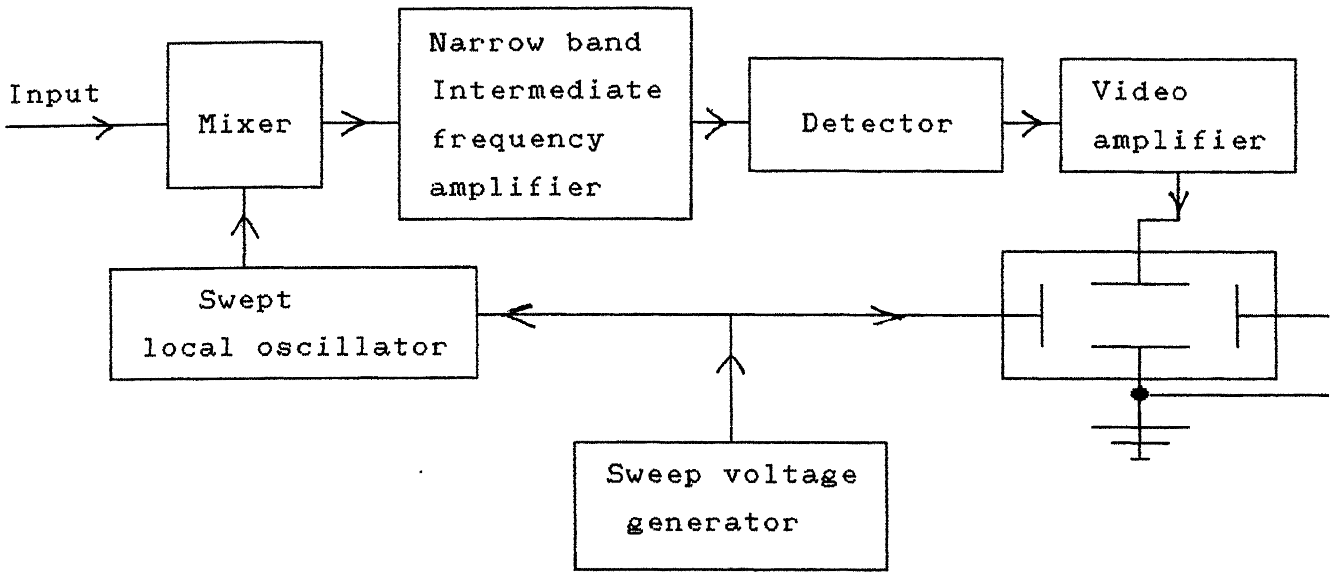


Figure 3.5: Schematic bloc diagram of swept front end type spectrum analyzer.

The upper portion of the block diagram in figure 3.5 represents essentially a superhetrodyne receiver except that local oscillator is electronically tuned which permits the magnitude of signals or radio noise to be displayed oscillographically on a linear frequency axis. A problem that can be encountered when using spectrum analyzer is that the absence of a selective or filtered input. This means that some large signals, in parts of the frequency spectrum which are far removed from the displayed range of interest, can cause overload problems. Spurious response within the analyzer and sweep rate through a frequency range are also important considerations.The spectrum analyzer used is SWEPT FRONT END TYPE. The spurious response problem is much alleviated in this system because the first IF amplifier being of the narrow band type, has been constructed for a much higher frequency. A higher IF amplifier frequency means greater frequency separation between the true response and the spurious response and hence lesser difficulties. However these problems can be overcome (as explained in appendix B) and spectrum analyzer can be used for the measurement of EMI.

<u>SPECIFICATIONS</u>:(On next page)

Table 3-1 Specifications of Spectrum Analyzer

1. Frequency

1.1 Measuring range

Frequency band	N*	1st IF Frequency
100k - 2GHz	1	2521.4 MHz
1.7G - 23GHz	1 to 4	Note

*N is harmonic mixing mode number defined

$f = N*f_{LO} \pm f_{IF}$

f:Measuring Frequency f_{LO}:1st Local Frequency

f_{IF} :1st IF Frequency

NOTE : N = 1 for f < 6.5 GHz, N = 2 for f < 12.5 GHz
N = 3 for f < 12.5 GHz, N = 4 for f > 18.5 GHz

1.2 Frequency span	Setting range and	1 kHz/div to 200 kHz/div in 1 kHz increments 210 kHz /div to 2 MHz/div in 10 kHz increments 2.1 MHz/div to 20 MHz/div in 100 kHz increments 21 MHz/div to 200 MHz/div in 1 MHz increments
Readout accuracy		± 5% (200 MHz/div to 6 kHz/div) ± 10% (5 kHz/div to 1 kHz/div)
1.3 Marker	Normal	Frequency difference between two marker displayed.
	D(delta)	Frequency difference between two marker positions displayed.
	Peak	Marker shows Peak Position and frequency displayed.
1.4 Resolution Resolution bandwidth (6 dB bndwidth)		100 Hz to 3 MHz in a 1,3,10 sequence May be selected manually or automatically coupled to frequency span

2. Amplitude	
2.1 Measuring Range	Average noise level to + 30 db
2.2 Display	
Graticule	Vertical 8 division,reference level top graticule.
LOG	
10 dB/div	0 to -70 dB from reference level
5 dB/div	0 to -40 dB from reference level
2 dB/div	0 to -16 dB from reference level
1 dB/div	0 to -18 dB from reference level
2.3 Reference Level	
Setting range	-109 dBm to + 30 dBm
Calibration output accuracy	- 10 dBm ± 0.3 dBm (100 MHz ± 10 kHz)
Reference level accuracy	± 2.0 dB
Frequency response	± 2.5 dB (100 kHz start frequency,10 MHz stop frequency) ± 1.5 dB (10 MHz start frequency, 2 GHz stop frequency)
2.4 Marker	
Normal	Level of the marker position displayed
D(delta)	Level difference between two marker position displayed
Peak	Marker shows peak position and level
2.5 Average noise level	< -95 dBm(100 kHz to 1 MHz) < -115 dBm (1 MHZ to 2 GHz) at 1 kHz RBW, 0 dB input attenuator

2.6 Video Bandwidth		1 Hz To 3 MHz, 1, 3, 10 sequence May be selected automatically or manually, coupled to frequency span
	Connector	N-type (nominal 50 w)
	Maximum Input level	+ 30 dBm
3 Sweep Time		2 ms/div to 10 S/div.Manual automatic coupling to frequency span, resolution bandwidth and video bandwidth can be selected.

3.3.2 SENSITIVITY of SPECTRUM ANALYZER:

Sensitivity is the rating factor of spectrum analyzer's ability to display weak signals. Sensitivity is usually specified as the signal power which equals the analyzer noise power at a particular bandwidth; this is determined by the method known as, "signal-plus-noise is equal to twice noise". Hence the Spectrum analyzer's noise level determines its sensitivity - less noisy amplifier means better sensitivity. A wider bandwidth means a poorer sensitivity. A spectrum analyzer should therefore be operated at narrow resolution bandwidth. This conclusion is correct for discrete CW signals but not for pulse signals which have continuous dense type spectrum. This is because for a discrete CW signal RBW should be less than the repetition frequency of signal and for continuous dense type spectrum RBW should be greater than the pulse repetition frequency. Only under the conditions mentioned above one can see fine details of dense continuous type spectrum. For EMI measurement due to corona with the help of spectrum analyzer high RBW is required because signals produced due to corona are impulse in nature. Hence use of high RBW brings down the sensitivity of the analyzer which is -95 dBm at 1 kHz RBW and '0' dB input attenuator, in the frequency range of 1 MHz to 2 GHz. In order to increase the sensitivity of the analyzer, amplifiers in cascade (details given in section 3.3.3) were used. Sensitivity of analyzer is increased by the gain of the amplifiers. As the amplifiers were used in cascade, noise figure of cascaded amplifiers increased slightly upto 8.51 dB (calculations are given in Appendix B) which brought down the sensitivity of the analyzer to some extent. Therefore it is recommended that instead of using cascaded amplifiers, a single amplifier of high gain and low noise figure should be used depending upon the user's range of frequency.

3.3.3 CABLE:

A 5 metre video cable (RG-55) having characteristic impedance of 50 Ω and N-type male connector connected at its both ends was used to connect different antennae to spectrum analyzer.

CABLE LOSS:

Cable losses were determined by feeding signal from a standard RF signal generator to the spectrum analyzer and noting down signal amplitude at different frequencies. At first a one metre standard, loss less cable was used & then actual cable was connected. Cable losses were determined at different frequencies by subtracting the signal amplitude at a particular frequency for actual cable to signal amplitude at that particular frequency for one metre cable. Table 3 - 2 (given on next page) gives the cable losses at various frequencies.

TABLE 3-2 Cable Losses

Frequency MHz	Signal Level of Generator shown by itself in dBm	Signal Amplitude For One Meter Cable in dBm shown by analyzer	Signal Amplitude For actual Cable dBm shown by analyzer	Cable Loss dBm
15	-57.2	-57.48	-57.84	0.36
25	-57.2	-57.92	-57.92	0.42
35	-57.2	-57.94	-57.98	0.42
65	-57.2	-57.56	-57.98	0.42
130	-57.2	-57.64	-58.10	0.46
250	-57.2	-57.68	-58.58	0.90
550	-57.2	-57.76	-59.77	1.94
750	-57.2	-57.80	-60.36	2.56
850	-57.2	-57.86	-60.92	3.06
1000	-57.2	-57.94	-61.31	3.37

3.3.4 AMPLIFIERS:

The performance of amplifiers whose details are given below qualifies them for a number of uses, for example, to improve the sensitivity of counters, spectrum analyzers, RF voltmeters, power meters and other devices without distortion or degradation of amplitude accuracy; to increase the maximum power available from a signal generator a 8447 E power amplifier was used. The characteristics of these amplifiers are following:

i) Wide Band.

ii) Flat Response.

i) Low Noise

ECIFICATIONS:

Table 3-3 Specifications of amplifier

	8447D Preamplifier	8447 E Amplifier
Frequency Range	100 kHz-1.3 GHz	100 kHz - 1.4 GHz
3 dB bandwidth	50 kHz - 1.4 GHz	50 kHz - 1.4 GHz
Gain (Mean)	26 dB ± 1.5 dB	22 dB ± 1 5 dB
Noise Figure	< 8.5 dB	< 11 dB
Impedance	50 Ω	50 Ω

3.5 ANTENNA:

Two broad band antennae were used to measure the level of EMI sociated with different types of coronas. These are:

) BICONICAL ANTENNA,MODEL. (25 TO 200 MHz)

) CONICAL LOGARITHMIC SPIRAL ANTENNA (200 TO 1000 MHz)

BICONICAL ANTENNA:

The STODDART BICONICAL ANTENNA, Model 94455-1 is a broad nd, balanced antenna designed to cover the frequency range of 25 200 MHz and calibrated for a 50 ohm load. The biconical tenna has been specifically designed for use with ectromagnetic Interference (EMI) measuring equipments. The conical antenna may also be used simply as a wide frequency nge antenna for various receiving equipments covering by part or mplete 25 to 200 MHz frequency range.

:CTRICAL DESCRIPTION:

The biconical antenna is very similar to the tunned dipole :enna with respect to its radiation pattern and mode of :ration as a balance system. However the antenna elements of : biconical antenna do not require adjustment with frequency as the case of a tuned dipole. This is due to the antenna ıfiguration, which has the general shape of a cone. The cone ;le and length have been selected to provide an antenna terminal)edance remaining essentially resistive i.e. resonant over a :y wide frequency range.

The biconical antenna terminal impedance is approximately 120 ms and is balanced. A loss less balun (balanced to unbalanced) ansformer is used to match antenna impedance to a 50 ohm balanced load.

ERATION:

The model 94455-1 biconical antenna is inherently broad band d requires no adjustment of length of the antenna elements. wever it has a radiation pattern similar to that of a tuned pole and must be positioned with its broadside towards the gnal source for maximum response. In addition, the antenna must rotated to obtain maximum response to signal polarization.

LIBRATION OF THE BICONICAL ANTENNA:

The antenna correction factors (ACF) graph is provided ong with the antenna for test sample positioned at one metre om antenna and when antenna is in the "far field". Figure 3.6 & 7 give graphs for antenna correction factor for near & far

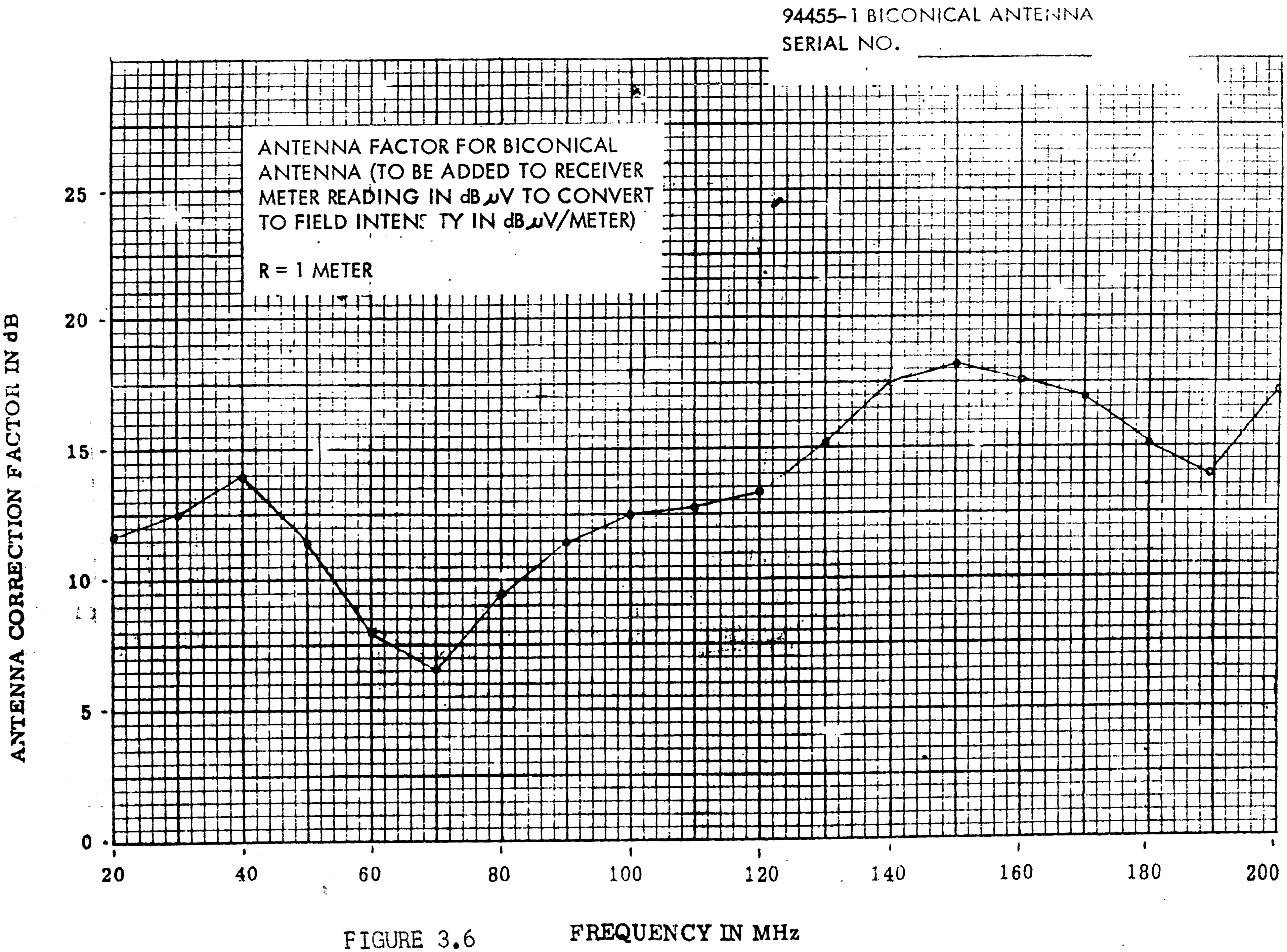

94455-1 BICONICAL ANTENNA
SERIAL NO.
ANTENNA FACTOR FOR BICONICAL ANTENNA (TO BE ADDED TO RECEIVER METER READING IN dBμV TO CONVERT TO FIELD INTENSITY IN dBμV/METER)
R = 1 METER
25
20
15
10
5
0
20
40
60
80
100
120
140
160
180
200
ANTENNA CORRECTION FACTOR IN dB
FREQUENCY IN MHz

FIGURE 3.6

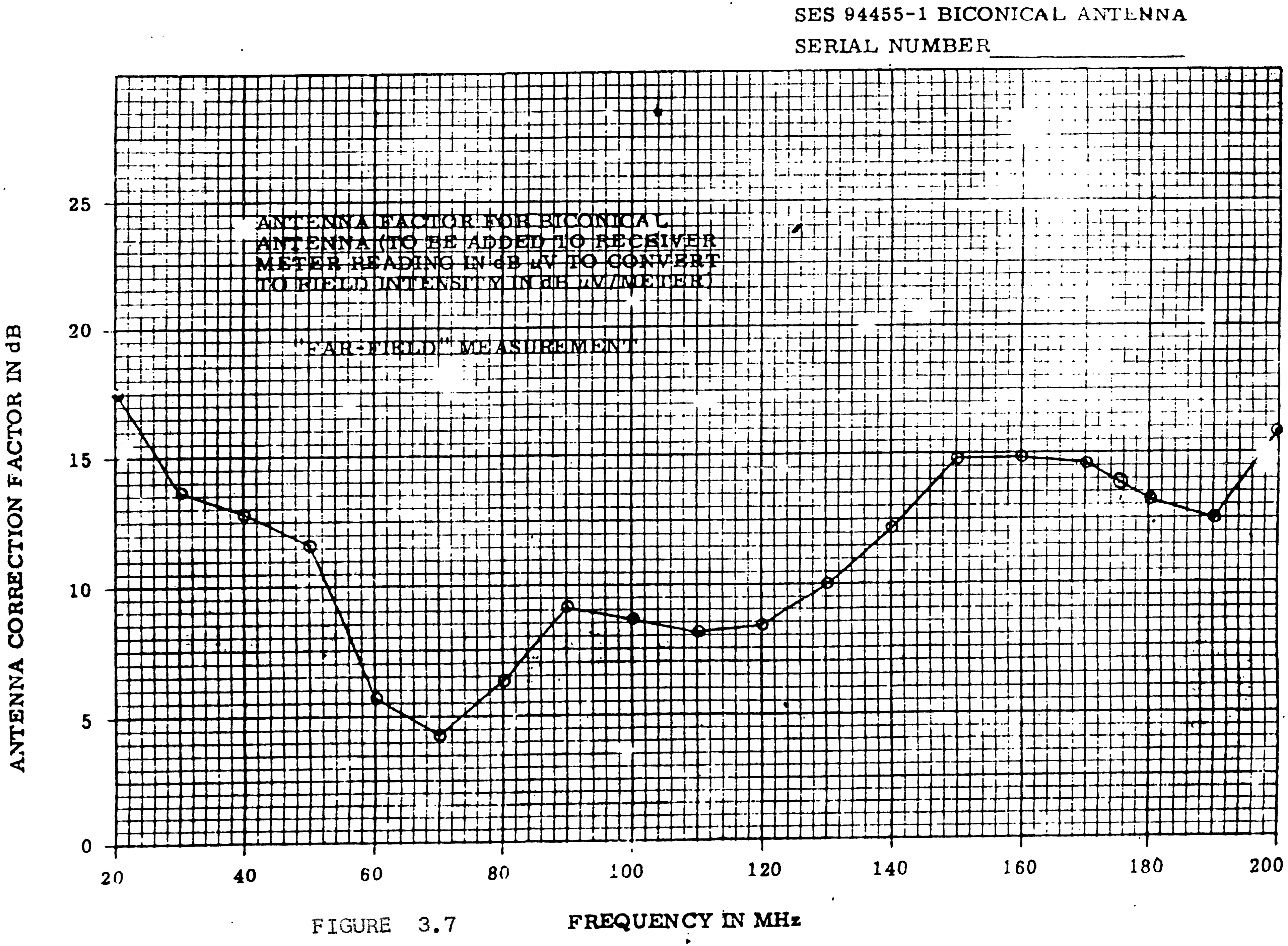

SES 94455-1 BICONICAL ANTENNA
SERIAL NUMBER
ANTENNA FACTOR FOR BICONICAL ANTENNA (TO BE ADDED TO RECEIVER METER READING IN dB µV TO CONVERT TO FIELD INTENSITY IN dB µV/METER)
"FAR-FIELD" MEASUREMENT
ANTENNA CORRECTION FACTOR IN dB
0
5
10
15
20
25
20
40
60
80
100
120
140
160
180
200
FREQUENCY IN MHz

FIGURE 3.7

fields.

MEASUREMENT:

In order to find out RF field strength (dB μv/m)due to a test sample, positioned at a distance of one meter from the antenna, add the dB value of the ACF (at the test frequency) to the EMI instrument measurement (across 50 ohm input) in dB above one micro volt.

Example:

Frequency----------------------------	60 MHz
Meter Reading------------------------	25 dB
Attenunuator Setting-----------------	20 dB
ACF----------------------------------	8 dB

RF field strength = 25 dB + 20 dB + 8 dB= 53 dB μV/m

It is recommended that if source is at such a distance that receiving antenna is in " far field " figure 4.6 should be made use to find out ACF. Otherwise, the same procedure is applicable as in deriving field strength in dBμV/ m described above.

ii) CONICAL LOGARITHMIC SPIRAL ANTENNA:

This antenna was chosen because the entire shape of it can be solely specified by angles making it truly a frequency independent antenna.

The STODDART, CONICAL LOGARITHMIC SPIRAL ANTENNA, No. 94490 is CIRCULARLY POLARISED and is equally sensitive to either horizontally or vertically polarized linear polarization or in between the two. Hence it does not require orientation for signal

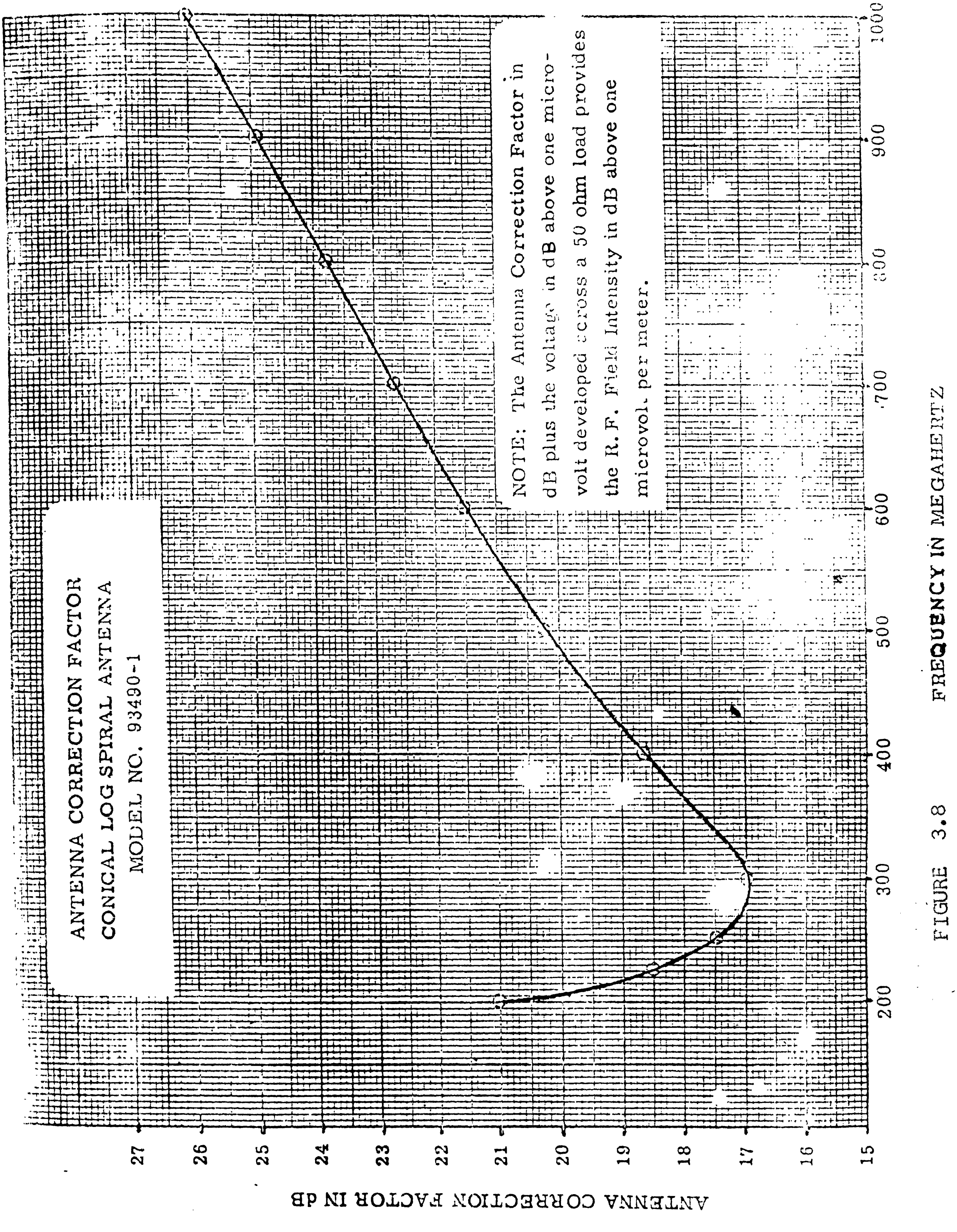

ANTENNA CORRECTION FACTOR
CONICAL LOG SPIRAL ANTENNA
MODEL NO. 93490-1
NOTE: The Antenna Correction Factor in dB plus the voltage in dB above one microvolt developed across a 50 ohm load provides the R. F. Field Intensity in dB above one microvolt per meter.
200
300
400
500
600
700
800
900
1000
15
16
17
18
19
20
21
22
23
24
25
26
27
ANTENNA CORRECTION FACTOR IN dB
FREQUENCY IN MEGAHERTZ

FIGURE 3.8

polarization.

The antenna correction factor for the 94490 were determined using the "Two Identical Antenna Gain" method for circularly polarized waves. The antenna correction factors graph (Frequency - Versus - Correction Factor in dB) is shown in Figure 3.8.

The antenna correction factor (given in terms of decibels) together with the voltage in dB above 1 μV developed across a 50 ohm load (receiver input) provides the RF field intensity in dB above 1 μV per meter (dB μV/meter).

EXAMPLE:

Frequency	500 MHz
Output Meter Reading	30 dB
Attenuator Setting	20 dB
Antenna Correction Factor	20.2 dB

Then the RF field intensity is equal to

$$30 + 20 + 20.2 = 70.2 \text{ dB } \mu V/m$$

3.3.6 TELEVISION :

One 51 cm colour television MAKE:BELTEK was used to see the effects of different types of coronas on TV picture. Two YAGI antenna were used. One antenna was used to receive TV transmission signals and another antenna was used to receive noise signals due to coronas and the output of both the antennae were fed simultaneously to TV. One transistor radio MAKE:UPTRON Model CHALENGER was also used to hear the effects of coronas on radio.It contained SW & MW (550 - 1650 kHz and 9 - 12.5 MHz).

3.4 INSTRUMENTATION FOR MEASUREMENT OF IMPULSE BANDWIDTH:

Measurement of impulse bandwidth [7] or bandwidth figure (dealt in detail in appendix B) was done with the help of set of measuring instruments. A block diagram for measurement is shown in section 4.2 in figure 4.1.

3.4.1 PIN MODULATOR:

It was used to produce RF pulses of desired width and frequency. The frequency of RF signal depends upon the range of frequencies in which PIN MODULATOR generates RF pulses.

SPECIFICATIONS:

MAKE :HP

MODEL:8403 A.

POWER REQUIREMENT:

115 or 230 VOLTS ± 10%, 50 TO 1000 cps

INTERNAL MODULATION:

SQUARE WAVE:

Frequency: Continuously variable from 50 cps to 50 kc, 3 decade ranges

PULSE:

Repetition Rate: Continuously variable from 50 cps to 50 kc,3 decade ranges.

Width: Continuously variable from 0.1 msec to 100 msec in 3 decade ranges.

EXTERNAL MODULATION:

PULSE INPUT:

Amplitude and polarity: 5 Volts to 15 VOlts, peak either positive or negative.

Repetition Rate: Maximum average prf, 1 Mc/sec, Maximum peak prf 2 Mc/sec.

Input Impedance: Approximately 2000 ohms.

Minimum Width: 0.1 msec.

Maximum Width: 1/prf - 0.4 msec

3.4.2 RF SIGNAL GENERATOR

It was used to feed CW signal to PIN MODULATOR to achieve RF pulse.

SPECIFICATIONS:(RF signal generator)

MAKE :HP.

MODEL:8614 A.

FREQUENCY RANGE:800 to 2400 MHz.

VERNIER:Δ F control has a minimum range of 1.5 MHz for fine tuning.

FREQUENCY CALIBRATION ACCURACY: ± 5 MHz.

RF OUTPUT POWER:+10 dBm (10 mw) into 50-Ω load output attenuation dial directly calibrated in dBm from 0 to -127 dBm. A second uncalibrated output (approximately 0.5 mW) is provided on front panel.

RF OUTPUT POWER ACCURACY (With Respect To Attenuation dial):

± 0.75 dB + attenuator accuracy (-15 to -127 dBm) including levelled output variations.

ATTENUATOR ACCURACY:+0,-3 dB from 0 to - 15 dBm; + 0.2 dB + 0.06 dB/10 from -15 to -127 dBm; direct reading dial,0.2 dB increments.

LEVELLED OUTPUT:Over entire frequency range at any attenuation setting below 0 dB:±0.75 dB. Output power adjustable with ALC CONTROL.

INTERNAL IMPEDANCE:50 Ω.

POWER SOURCE:115 or 230 V ± 10 %, 50 to 60 Hz.

3.4.3 PULSE GENERATOR:

A pulse generator was used to obtain pulses of pulse width 0.1 μsec,1/ 3 μsec and prf (pulse repetition frequency) of 225 kHz and 75 kHz respectively. Pulses were fed externally to PIN MODULATOR because maximum prf of internal pulse generated by PIN modulator was 50kHz only.

SPECIFICATIONS:

Make:HP

Model:8082 A

TRANSITION TIMES:≤ 1 ns to 0.5 ms in 6 ranges. First range from ≤ 1 ns to 5 ns controls leading and trailing edges simultaneously. For all other ranges transition time variable independently.

OUTPUT: Maximum output voltage is ± 5 V.

POWER REQUIREMENT:100 V, 120 V, 220 V,240 V (+ 50 - 10%) 48-440 Hz.

3.4.4 SPECTRUM ANALYZER:

To find out the spectral intensity of impulse signal occurring due to coronas impulse calibration of spectrum analyzer was done. This is nothing but to measure impulse bandwidth or Bandwidth Figure for a particular Resolution Bandwidth. Rest details of spectrum analyzer are given in section 3.3.1.

3.4.5 OSCILLOSCOPE:

A digitizing oscilloscope, which can measure maximum frequency upto 100 MHz, was used to measure pulse width of 1/ 3 μsec, 0.1 μsec and prf of 75 kHz and 225 kHz respectively. The pulses 1/ 3 μsec, 75 kHz & 0.1 μsec 225 kHz were used for measurement of impulse bandwidth of spectrum analyzer for 300 kHz and 1 MHz Resolution Bandwidths.

SPECIFICATIONS:

MAKE: HP.

MODEL: 54200 A/D Digitizing Oscilloscope.

VERTICAL: (Channel 1 and 2)

RANGE: 40 mV to 40 V full scale.

TIME BASE: (Horizontal)

RANGE: 50 ns to 10 sec full scale (10 division)

TIME MEASUREMENT ACCURACY: + 2 ns or + 0.2% of Time Range whichever is greater.

TRIGGER: (Analog)

SOURCES: Channel 1, Channel 2 or External Trigger Level Range/Resolution :

Full-Scale Range	Trigger Range
40 mV to 390 mV	± 2 V.
400mV to 40 Volt	± 20 V.

CHAPTER 4

MEASUREMENT TECHNIQUES AND RESULTS

In this chapter the measurement techniques of EMI associated with different types of coronas are described. In the beginning, problems associated with spectrum analyzer during measurement has been discussed. The method of impulse calibration of spectrum analyzer for a particular Intermediate Frequency (IF) or Resolution Bandwidth (RBW); which should be done before starting the EMI measurements, has been described and evaluated. The setup was then made ready for the measurement of level of EMI due to various types of coronas with the help of spectrum analyzer, antennae and amplifiers. Towards the last stage of measurement, the effect of coronas on TV picture in VHF range, i.e. on channel IV at 175.25 MHz has been reported.

4.1 MEASUREMENT TECHNIQUES:

To measure level of radio noise associated with different types of coronas, two broadband antennae, Biconical and Spiral Log Cone type which cover frequency ranges from 25 to 200 MHz and 200 to 1000 MHz respectively, were used. The Biconical antenna terminal impedance is approximately 120 ohms and is balanced. A loss less balun (balanced-to-unbalanced) transformer is used to match the antenna impedance to a 50 ohm unbalanced load. The spiral log cone antenna also has its output impedance of 50 ohms. Since the spectrum analyzer also has a 50 ohms impedance the incoming signal could be conveniently received by the spectrum analyzer. The antenna's could be connected through amplifier to the spectrum analyzer if necessary. In this way antenna's bandwidth provided a selective or filtered input to the analyzer which prevented overload problem and enabled accurate assessment of the analyzer performance.

The performance of spectrum analyzer was checked by feeding a calibration continuous wave (CW) signal of 100 MHz and -10 dBm available at one point on its front panel. The accuracy of this signal was given to be -10 dBm ± 0.3 dBm at 100MHz ± 10kHz. According to the spectrum analyzer's pamphlet, it would not work if calibration signal is not displayed properly on the CRT of the analyzer. Continuous checks were made to prevent overloading of the analyzer and for any spurious response. For example when input attenuation was increased by 10 dB the magnitude of display on CRT should not reduce by more than 10 dB.

The pulses produced due to ac coronas are broad band impulse signals having a continuous frequency spectra. Table 4.1 distingushes the major differences between the two types of displays i.e. continuous wave or discrete spectrum (CW - type spectrum) and continuous - type spectrum.

Table 4.1 Major difference between discrete CW and dense continuous type spectrum.

CW - TYPE SPECTRUM	CONTINUOUS TYPE SPECTRUM
LINES ON SCREEN ARE FOURIER SPECTRAL COMPONENTS	LINES ON SCREEN ARE REPETITION RATE LINES
LINE SPACING DEPENDS UPON DISPERSION SETTING AND IS INDEPENDENT OF SWWEP TIME	LINE SPACING IS DETERMINED BY SWEEP TIME AND IS INDEPENDENT OF DISPERSION SETTING
MATHMATICAL DESCRIPTION IS FOURIER SERIES	MATHMATICAL DESCRIPTION IS FOURIER INTEGRAL
RESOLUTION SETTING (B) < REPETITION RATE	RESOLUTION SETTING (B) > REPETITION RATE
THE CRT DISPLAY SHOWS THE RESOLUTION AMPLIFIER STEADY STATE RESPONSE	THE CRT DISPLAY SHOWS THE RESOLUTION AMPLIFIER TRANSIENT RESPONSE
THERE EXISTS A RESIDUAL ENERGY IN THE CIRCUIT FROM PREVIOUS PULSE WHEN THE NEXT PULSE OCCURS	ALL THE ENERGY IN THE CIRCUIT FROM THE PREVIOUS PULSE HAS DECAYED TO ZERO WHEN THE NEXT OCCURS
THE PRODUCT OF BANDWIDTH AND PULSE WIDTH $(B\ t_o) > 1$	BANDWIDTH AND PULSEWIDTH PRODUCT $(B\ t_o) < 1$

Impulse signals are measured in terms of their spectral intensity in Volts/ MHz or dB above one micro volt per MHz. In order to convert broad band impulse signal's amplitude given in dBm into their spectral intensity 'S', the Bandwidth Figure B for the appropriate Resolution Bandwidth (RBW) should be subtracted from the amplitude displayed by analyzer. It is explained as follows:

(The analyzer displays absolute amplitude in dBm. One μV is ıual to - 107 dBm)

$$S\ (dB\ \mu V/\ MHz\ ) = V\ (in\ dBm\ ) - B\ (in\ dB\ MHz) + 107 \quad \ldots\ldots\ldots(4.1)$$

Measurement of broadband impulse signal and spectrum analyzer ›erations are discussed in detail in Appendix B.

.2 PROCEDURE FOR DETERMINING BANDWIDTH FIGURE B (For use with he logarithmic mode):

Bandwidth Figure B (in dBMHz) = 20 log BW_i/ 1 MHz

Where BW_i = Impulse Bandwidth.

Impulse bandwidth for each IF bandwidth setting should be easured at different signal levels in 10 dB steps and the average alue should be used to determine Bandwidth Figure B. The easurement setup is shown in Figure 4.1

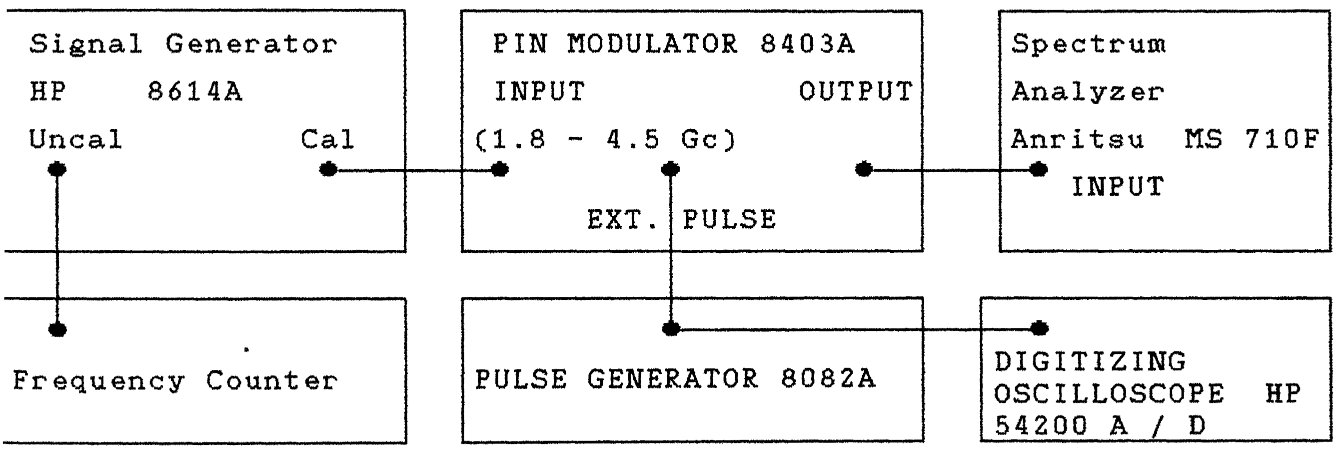


Figure 4.1 Setup for Impulse Bandwidth Measurement

The performance of PIN MODULATOR should be checked before aking the impulse bandwidth measurement. Performance check for ne same is given in Appendix B equation (4).

Impulse bandwidth BW_i can be determined from Equation 14 of ne Appendix B. This yields

$BW_i = (10^{(V_p - V_1)/ 20})/ \tau$ ....(4.2)

nere

BW_i is in Hz, V_p and V_1 in dBm and τ in time unit.

$B = 20 \log BW_i / 1$ MHz ....(4.3)

The pulse width τ (Pulse obtained from external pulse enerator) for nominal bandwidths of 300 kHz and 1 MHz were easured directly on oscilloscope as well as indirectly by easuring the frequency distance of the main lobe zeros of the isplayed spectrum. The pulse width τ is measured indirectly for ominal bandwidths of 10, 30 and 100 kHz by measuring the requency distance of the main lobe zeros of the displayed pectrum. A detailed step by step procedure is given in the ollowing section to determine V_p and V_1 in dBm to be substituted n equation (4.2) to determine BW_i. It is then substituted in quation 4.3 to obtain the Bandwidth Figure B in terms of dB MHz. he steps are following:

. Set RESOLUTION BANDWIDTH control to appropriate bandwidth; ignal generator to RF; INTERNAL ALC and Frequency to 2000 MHz.

. Calculate Pulse width 'τ', $1 / \tau = 10 \times$ RBW.

For 10,30, and 100 kHz RBW

. Set modulator to internal Pulse RATE and WIDTH specified in Figures 4.2, 4.3, and 4.4 corresponding to the above RBW.

. Adjust width control of modulator until the distance between both the zeros adjacent to the main lobe of the displayed spectrum is as specified in the Figures 4.2, 4.3, & 4.4

. Note down V_p the peak value of main lobe in dBm.

. Note exact location of left and right zeros adjacent to main lobe of the spectrum on the CRT of analyzer. Half of the inverse of modulus of difference of both the zeros gives the pulse width τ

. Turn pulse modulation off by switching modulator to EXTERNAL AM.

. Read amplitude of CW signal V_1 in dBm on CRT of analyzer

. Using equations 4.2 & 4.3 find out BANDWIDTH FIGURE B in terms of dBMHz.

For 300 kHz and 1 MHz RBW

3. Set modulator to EXTERNAL PULSE

4. Set pulse generator output to 5 Volt, max .

5 Set the pulse generator until the length of one period on oscilloscope CRT is equal to f_3 for corresponding RBW shown in figure 4.5 and 4.6. Pulse width should not be greater than the inverse of pulse repetition frequency.

6 Adjust rate of pulse generator to value specified in figures 4.5, 4.6.

7 Adjust width control of pulse generator until width of pulse on oscilloscope CRT is exactly the length obtained in point 4 above.

8 Now feed the output of pulse generator to PIN MODULATOR.

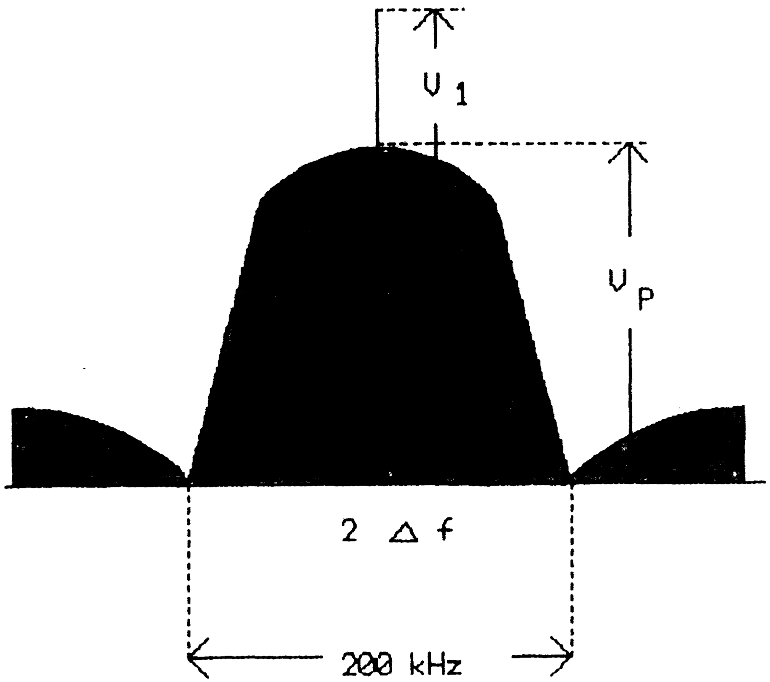
9 Note down, V_p the peak value of main lobe in dBm.

10 Note down the exact location of left and right zeros, adjacent to the main lobe of the spectrum. on the CRT of analyzer. Inverse of the modulus of difference of centre frequency and either left or right zero gives the pulse width τ.

11 TURN EXTERNAL PULSE MODULATION OFF by switching modulator to EXTERNAL AM.

12. Read amplitude of CW signal V_1 in dBm on CRT of analyzer.

13. Using equation 4.2 & 4.3 find out BANDWIDTH FIGURE IN TERMS OF dBMHz.



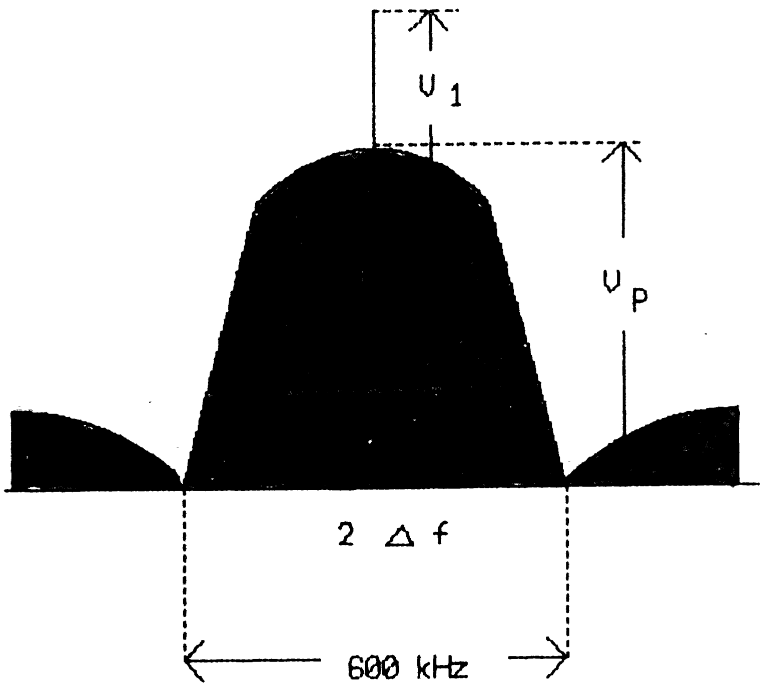
ANRITSU MS 710 F		
CENTRE FREQUENCY: 2000 MHz		
RESOLUTION BANDWIDTH	FRWQUENCY SPAN / DIVISON	VERT. DISPLAY
10 kHz	50 kHz	LOG

MODULATION RATE ≈ 2.5 kHz

MODULATION WIDTH ≈ 10 μ Sec

NULL SEPERATION $2 \Delta f$ ≈ 200 kHz

Figure 4.2

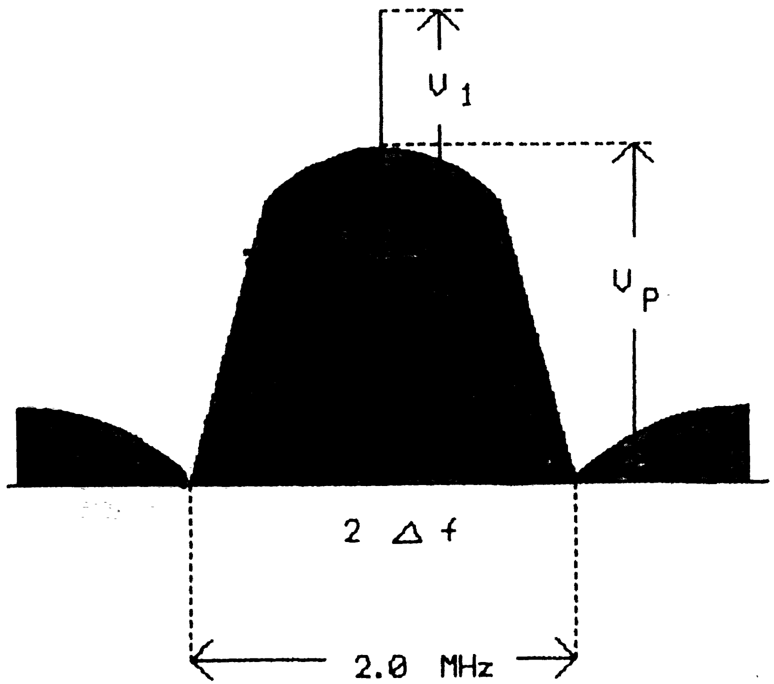


ANRITSU MS 710 F		
CENTRE FREQUENCy: 2000 MHz		
RESOLUTION BANDWIDTH	FRWQUENCY SPAN / DIVISON	VERT. DISPLAY
30 kHz	200 kHz	LOG

$f_3 \approx$ 300 kHz

MODULATION RATE $\approx$ 8 kHz

Figure 4.3



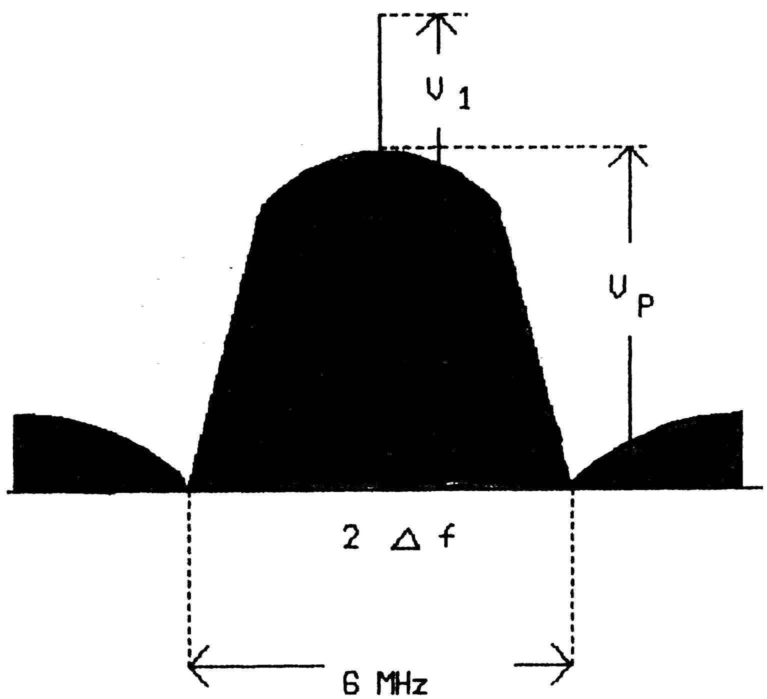
ANRITSU MS 710 F		
CENTRE FREQUENCY: 2000 MHz		
RESOLUTION BANDWIDTH	FRWQUENCY SPAN / DIVISON	VERT. DISPLAY
100 kHz	500 kHz	LOG

MODULATION RATE ≈ 25 kHz

MODULATION WIDTH ≈ 1 μSec

NULL SEPERATION 2 Δf ≈ 2.0 MHz

Figure 4.4

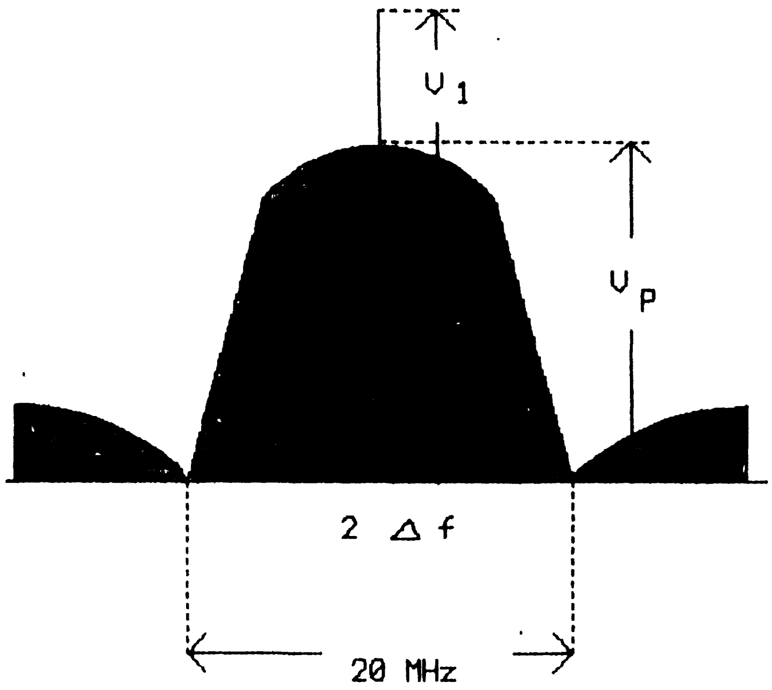


ANRITSU MS 710 F		
CENTRE FREQUENCy: 2000 MHz		
RESOLUTION BANDWIDTH	FRWQUENCY SPAN / DIVISON	VERT. DISPLAY
300 kHz	1 MHz	LOG

$f_3 \approx 3$ MHz

MODULATION RATE $\approx$ 75 kHz

Figure 4.5



ANRITSU MS 710 F		
CENTRE FREQUENCY: 2000 MHz		
RESOLUTION BANDWIDTH	FRWQUENCY SPAN / DIVISON	VERT. DISPLAY
1 MHz	5 MHz	LOG

$f_3 \approx 10$ MHz

MODULATION RATE $\approx$ 250 kHz

Figure 4.6

1.3 OBSERVATION TABLE:(For measurement of impulse bandwidth):

TABLE. 4.2, For 10 kHz RBW .

SET No.	Reference Level (dBm)	V_1 dBm	V_p dBm	τ μsec	BW_i Calculated	BANDWIDTH FIGURE (B) Calculated
1	20	9.32	-5.2	10	18.8 kHz	- 34.516 dB MHz
2	10	-2.6	-17.0	10	19.01 kHz	- 34.42 dB MHz
3	0	-12.2	-26.4	10	19.49 kHz	- 34.2 dB MHz

SAMPLE CALCULATION FOR SET No. 1:

$$BW_i = 10^{(-5.2 - 9.32)/20} / 10 \times 10^{-6} = 10^{-14.56} / 10^{-5}$$

$$BW_i = 18.8 \text{ kHz.}$$

$$B \text{ (dBMHz)} = 20 \log BW_i / 1 \text{ MHz} = 20 \log 18.8 \times 10^3 / 1 \times 10^6$$

$$= -34.516 \text{ dBMHz.}$$

Average B = - 34.42 dBMHz.

TABLE. 4.3, For 30 kHz RBW.

SET No.	Reference Level (dBm)	V_1 dBm	V_p dBm	τ msec	BW_i Calculated	BANDWIDTH FIGURE (B) Calculated
1	20	8.4	-4.8	1 / 3	65.63 kHz	- 23.65 dB MHz
2	10	-2.0	-15.0	1 / 3	67.16 kHz	- 23.45 dB MHz
3	0	-12.4	-25.5	1 / 3	68.72 kHz	- 23.25 dB MHz

Average B = - 23.45 dBMHz.

TABLE. 4.4, For 100 kHz RBW.

SET No.	Reference Level (dBm)	V_1. dBm	V_p dBm	τ μsec	BW_i Calculated	BANDWIDTH FIGURE (B) Calculated
1	20	8.8	-6.8	1	165.90 kHz	- 15.6 dB MHz
2	10	-8.2	-23.6	1	169.82 kHz	- 15.4 dB MHZ
3	-10	-19.5	-35.0	1	167.88 kHz	- 15.5 dB MHZ

Average B = - 15.5 dBMHz.

Setting of pulse generator 8082A is given in table 4.5 to obtain pulse of width 1 / 3 μsec having repetition frequency of 75 kHz required for the measurement of Impulse Bandwidth of spectrum analyzer at 300 kHz. On feeding the pulse described above to the PIN modulator, the observations made on the spectrum analyzer are tabled in table 4.6.

Table 4.5, Setting of pulse generator for pulse width of 1 / 3 μsec and frequency 75 kHz.

PULSE PERIOD	10 μ - 0.1 m sec
VERNIER	2 - 3 div (CW)
PULSE DELAY	2 n - 5 n sec
VERNIER	ccw (2 n)
PULSE WIDTH	50 n - 0.5 μ sec
VERNIER	6 - 7 div (cw)
NORMAL / DOUBLE PULSE SWITCH	NORMAL
MODE SWITCH	NORM
TRANSITION TIME	50 n - 0.5 μ sec
LEADING EDGE	MID - RANGE
TRAILING EDGE	MID - RANGE
AMPLITUDE	2.0 - 5.0 volt
VERNIER	CW.
OFFSET ON / OFF SWITCH	OFF
NORMAL / COMP SWITCH	NORM
NEG / POSITIVE SWITCH	POS

Table. 4.6, For 300 kHz RBW.

SET No.	Reference Level (dBm)	V_1 dBm	V_p dBm	τ μsec	BW_i Calulated	BANDWIDTH FIGURE (B) Calculated
1	20	9	-5.6	1 / 3	55.6 kHz	- 5.05 dBMHz
2	10	-2	-16.7	1 / 3	55.23 kHz	- 5.15 dBMHz
3	0	-13	-27.6	1 / 3	55.62 kHz	- 5.05 dB MHz

Average B = - 5.08 dB MHz.

Setting of pulse generator 8082A is given in table 4.7, to obtain pulse of width 0.1 μsec having repetition frequency of 225 kHz required for the measurement of Impulse Bandwidth of spectrum analyzer at 1.0 MHz RBW. On feeding the pulse described above to the PIN modulator the observations made on the spectrum analyzer are tabled in table 4.8 .

Table 4.7, Setting of pulse generator for pulse width of 0.1 μsec and frequency 225 kHz.

PULSE PERIOD	1 μ - 10 μ sec
VERNIER	4th div (CW)
PULSE DELAY	2 n - 5 nsec
VERNIER	ccw (2 n)
PULSE WIDTH	50 n - 0.5 μ sec
VERNIER	2nd div (cw)
NORMAL / DOUBLE PULSE SWITCH	NORMAL
MODE SWITCH	NORM
TRANSTION TIME	50 n - 0.5 μ sec
LEADING EDGE	MID - RANGE
TRAILING EDGE	MID - RANGE
AMPLITUDE	2.0 - 5.0volt
VERNIER	CW.
OFFSET ON / OFF SWITCH	OFF
NORMAL / COMP SWITCH	NORM
NEG / POSITIVE SWITCH	POS

Table. 4.8, For 1.0 MHz RBW.

SET No.	Reference Level (dBm)	V_1 dBm	V_p dBm	τ μsec	BW_i Calculated	BANDWIDTH FIGURE (B) Calculated
1	20	8.8	-7.00	0.1	1.62 MHz	4.19 dBMHz
2	10	- 2	-18.2	0.1	1.54 MHz	3.75 dBMHz
3	0	-12	-28.0	0.1	1.58 MHz	3.97 dBMHz

Average B = 3.97 dB MHz.

Following table 4.9 gives the measured results of average Impulse Bandwidth and Bandwidth Figure for different Resolution Bandwidths.

Table 4.9, Measured results of average Impulse Bandwidth and Bandwith Figure.

RBW	Average IMPULSE BANDWIDTH BW_i	Average BANDWIDTH FIGURE B
10 kHz	19.1 kHz	- 34.4 dB MHz
30 kHz	67.17 kHz	- 23.45 dB MHz
100 kHz	167.88 kHz	- 15.5 dB MHz
300 kHz	556.48 kHz	- 5.08 dB MHz
1 MHz	1.58 MHz	3.97 dB MHz

The bandwidth correction factor (B) in dB MHz is determined with the help of equation 4.2 .

NOTE: On top of every oscillogram showing frequency spectrum, frequency range is given in the form F:... MHz to ... MHz. In some figures instead of the frequency range centre frequency and frequency span is given on the top in the form F:...MHz SP: ... MHz / div.This represents that the centre frequency is x MHz and frequency span is y MHz / division, where x and y are any real number.The noise picked up by antenna from surrounding atmosphere (when corona source is not there) and internally produced by any component in the circuit i.e. amplifiers and spectrum analyzer is referred as Basic Noise.

4.4 MEASUREMENT OF EMI DUE TO GLOW CORONA:

The experimental setup for the measurement of level of radio noise or EMI due to *glow corona* is shown in Fig. 4.7 and 4.8 for the frequency range from 25 to 200 MHz and 200 to 1000 MHz respectively. The setup for the generation of *glow corona* has

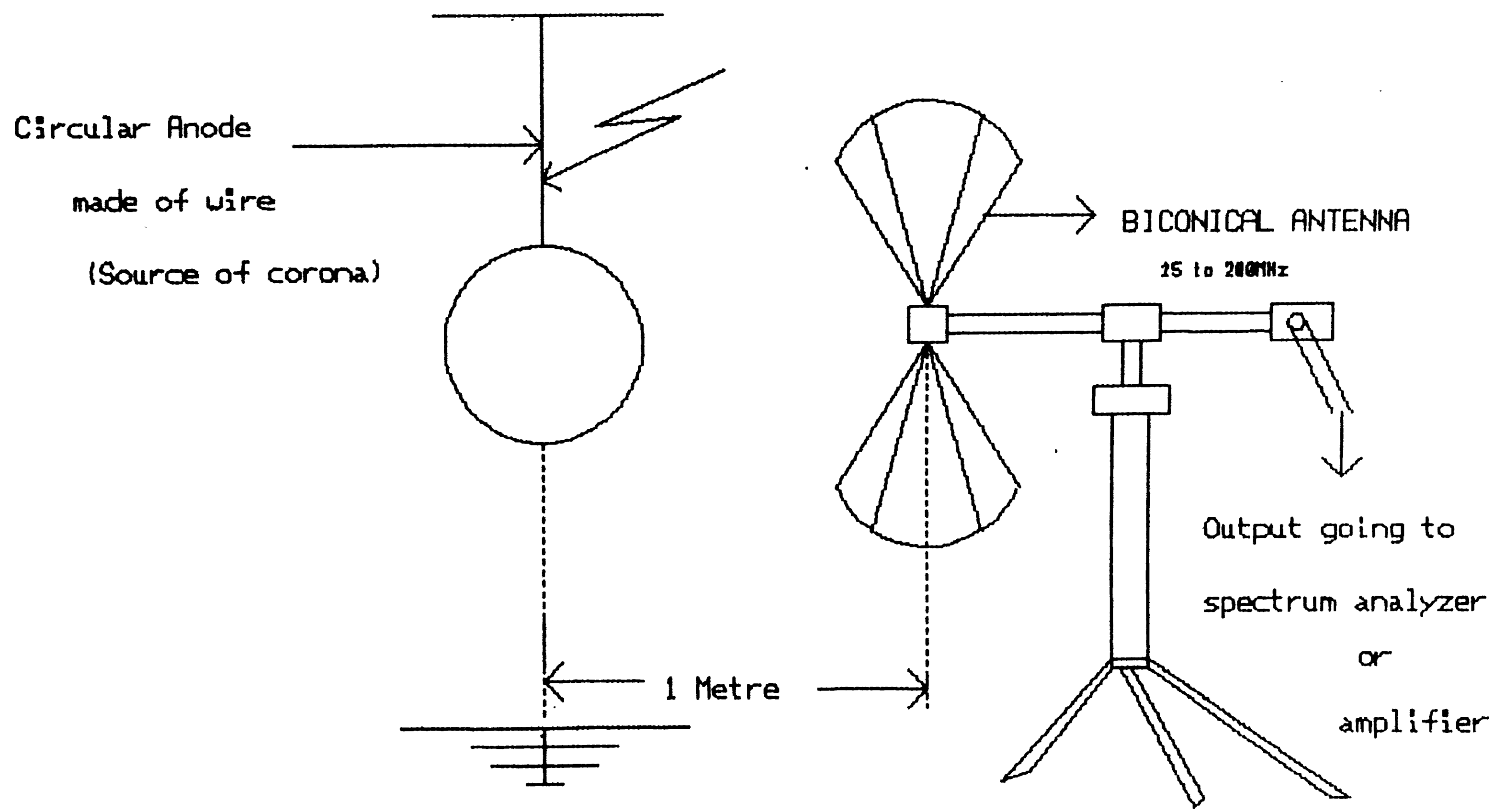


Fig.4.7 :Setup for measurement of EMI due to glow corona in the frequency range of 25 to 200 MHz.

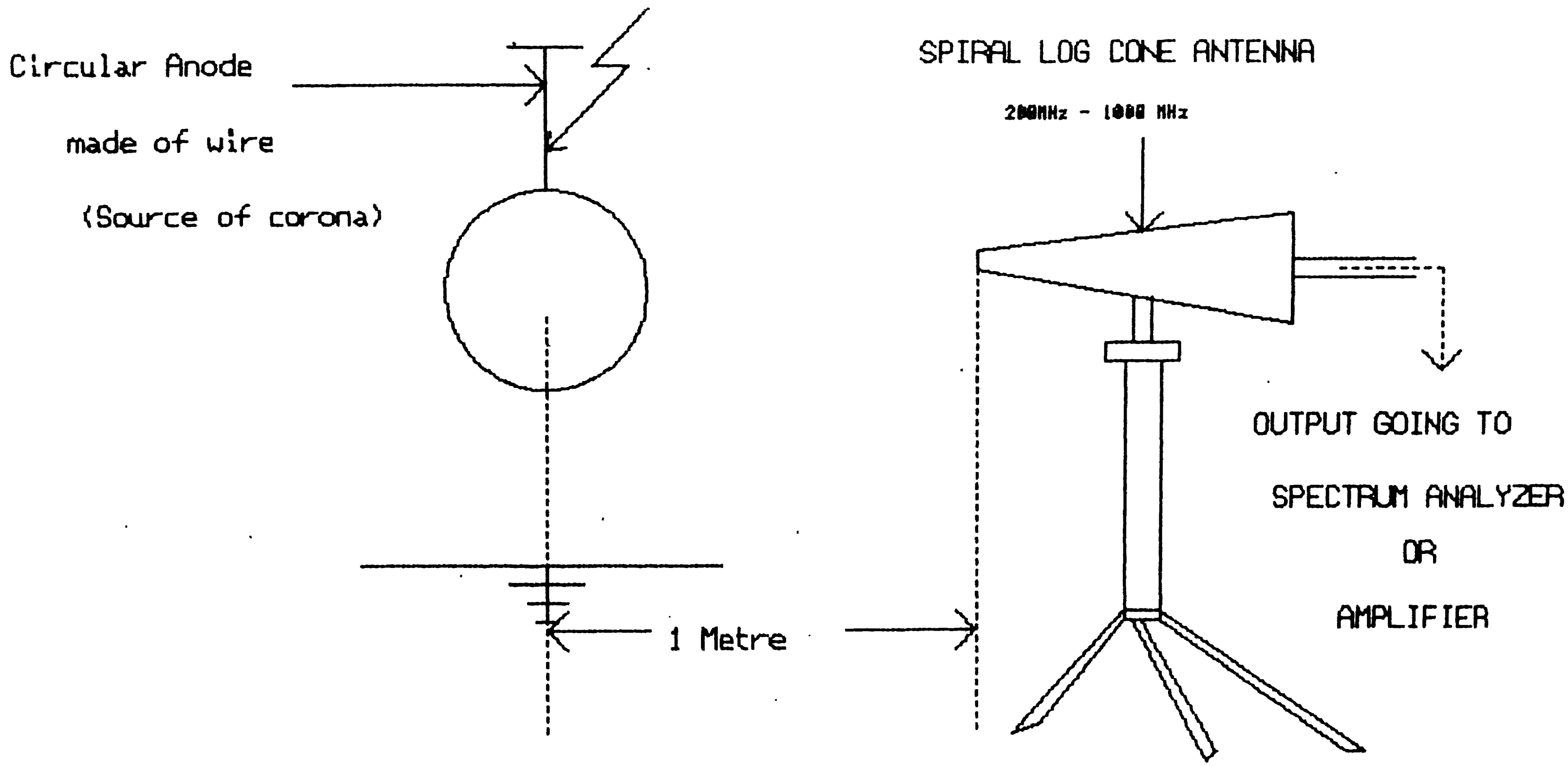


Fig.4.8: Setup for measurement of EMI due to glow corona in the frequency range of 200MHz to 1GHz

been discussed in section 3.2.1. The *glow corona* produced around a circular fuse wire which generated higher intensity of interference compared to glow at a single point electrode. Figures 4.9 to 4.13 show the frequency spectrum of radio noise level recorded due to *glow corona* in the frequency range of 20 to 1000 MHz. These observations were made at 45 kV and without any amplifier connected to the spectrum analyzer. Figure 4.14 to 4.15 show the noise level picked up by antenna (corona source off) and internally generated by spectrum analyzer at respective frequency range. If we compare the figure 4.9 to 4.13 with 4.14 to 4.15, we find that amplitude of noise level due to *glow corona* is equal to the noise level of the analyzer and antenna. This demonstrates that spectrum analyzer is not sensitive enough to display the radio noise level due to *glow corona*. As the antenna and spectrum analyzer together had level of - 65 dBm in the frequency range of 25 to 1000 MHz, one can say that noise level due to *glow corona* at 45 kV produced by the given setup was less than - 65 dBm / m (42 dB μV / m or 125 μV / m).

The intensity of noise due to *glow corona was* observed to be low. As a result it was not detectable on the CRT of the analyzer. In order to increase the sensitivity of the analyzer amplifiers were used. The antenna was connected through preamplifier-8447D to increase the signal strength and the output of preamplifier was fed to power amplifier-8447E to boost the signal power to be fed to the spectrum analyzer. The detail of these amplifiers are discussed in section 3.3.3 .

Figure 4.16 shows the frequency spectrum of the basic noise.

?igure 4.17 shows the frequency spectrum of noise due to *glow* :*orona* at 10 kV. In this figure inception of *glow corona* is :ecorded which has been marked by dotted lines at 43.5 and 48.5 IHz etc. As the voltage was raised from 10 kV to 45 kV, the intensity of noise due to *glow corona* also increased. Figure 4.18 shows the frequency spectrum of basic noise. Figure 4.19 shows frequency spectrum the of radio noise level at 45 kV for *glow* :*orona*. On comparing figures 4.18 and 4.19, it is revealed that :he noise level is maximum in the frequency range from 25 to 40 IHz and it decreases beyond this frequency. The frequency range between 174 and 180.25 MHz was of special interest for us in Kanpur because Kanpur Doordarshan video signal is transmitted in this frequency range. On comparing figures 4.19 with 4.18 it is clearly seen that noise level due to *glow corona* is about - 38 dBm. The effect of this noise was recorded on the TV screen during transmission later.

On comparing the two figures 4.20 and 4.21 which show frequency spectrum of the noise due to *glow corona* and basic noise respectively it is observed that the *glow corona* noise is absent on intermittent frequency bands. Similar results were also measured at higher frequencies shown in figures 4.22 and 4.24. Figure 4.23 and 4.25 are provided to enable comparison with basic noise level. No noise due to glow corona is present in the frequency range of 600 to 1000 MHz as observed from figure 4.26 after comparing with figure 4.27. From the above measurement it is clearly observed that noise due to glow corona is completely absent beyond 480 MHz.

Radio noise due to *glow corona* a is broad band signal. Its spectral intensity is estimated for an amplitude level equal to - 18 dBm at 29 MHz read from the figure 4.19 .

SAMPLE CALCULATION FOR SPECTRAL INTENSITY:

Spectral intensity (S) = Amplitude displayed by analyzer - Amplifier Gain + Cable Loss + Antenna Correction Factor (At 29 MHz) - Bandwidth Correction Factor (B) + 107 ....(4.4)
(dB µV/m MHz)

NOTE: In equation (4.4) all the quantities are in dBm except Antenna correction factor in dB µV and Bandwidth Correction Factor (B) in dB MHz. Number 107 in equation (4.4) is conversion factor from dBm to dB µV.

Pre-Amplifier Gain = + 26 dBm.

Power Amplifier Gain = + 22 dBm

Cable Loss = 0.42 dBm

Antenna Correction Factor = 14 dB µV

Bandwidth Correction Factor (for 300 kHz) = - 5.08 dB MHz.

$$S = -18 - 26 - 22 + 0.42 + 14 - (-5.08) + 107 =$$

$$= 60.58 \text{ dB } \mu V/(m \text{ MHz}).$$

Calculated spectral intensity 60.58 dB µV/(m MHz) can also be measured by a Voltmeter which measures the rms value of the broad band signal around 29 MHz.

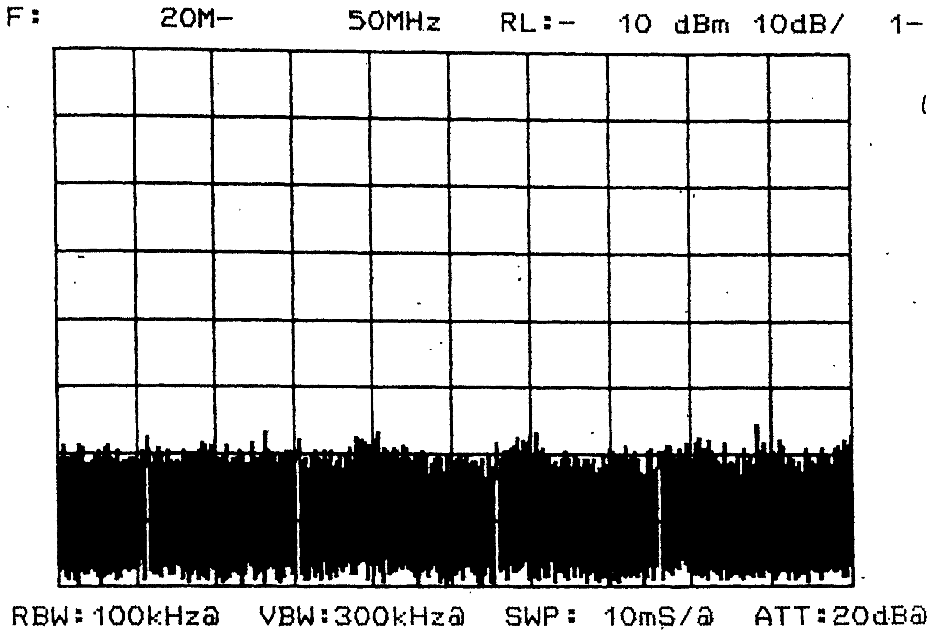


Fig. 4.9 : Frequency spectrum of EMI due to glow corona at 45 kV, no amplifier in circuit.

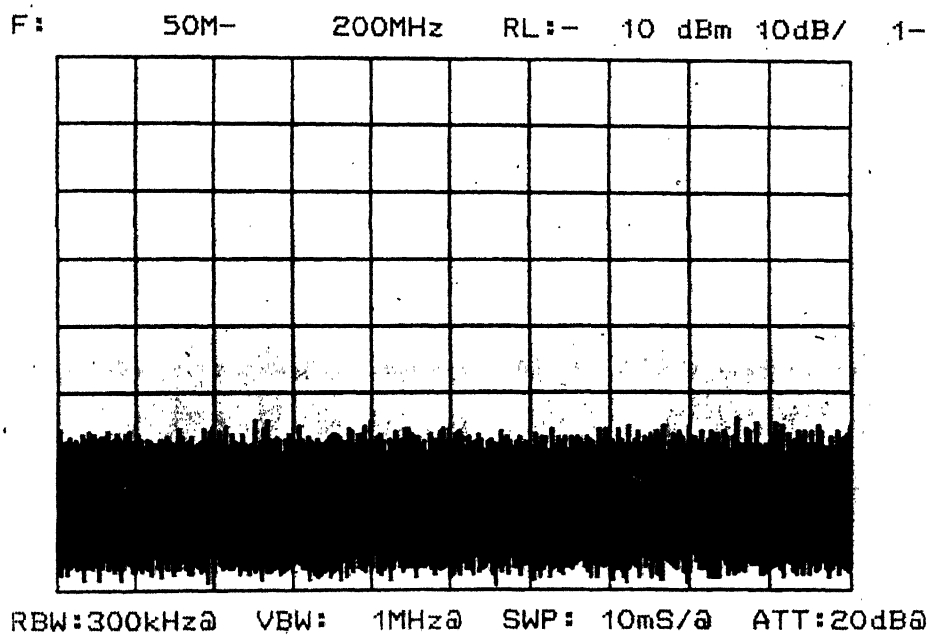


Fig. 4.10 : Frequency spectrum of EMI due to glow corona at 49 kV, no amplifier in circuit.

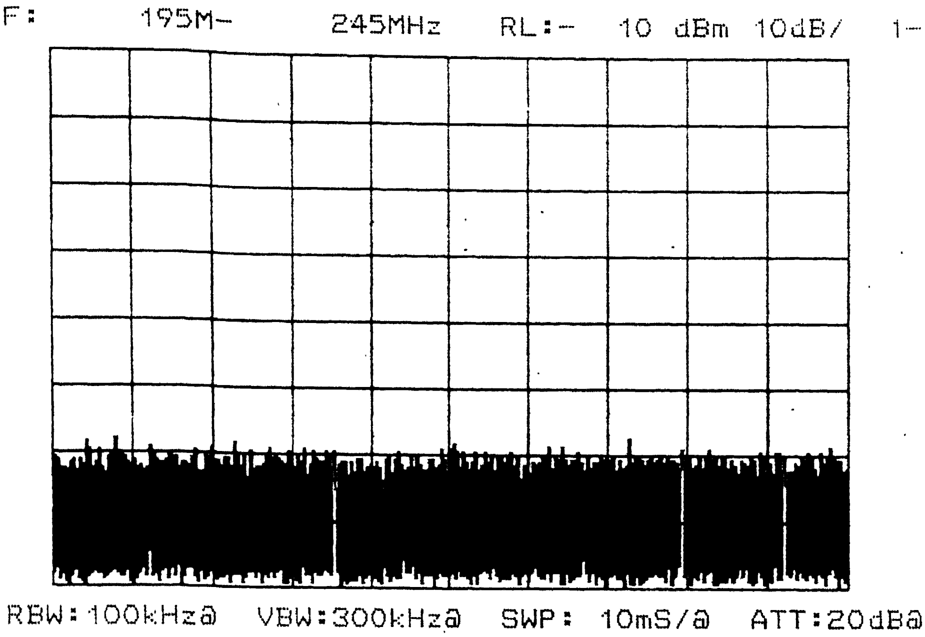


Fig. 4.11 : Frequency Spectrum of EMI due to glow corona at 45 kV without amplifier in circuit.

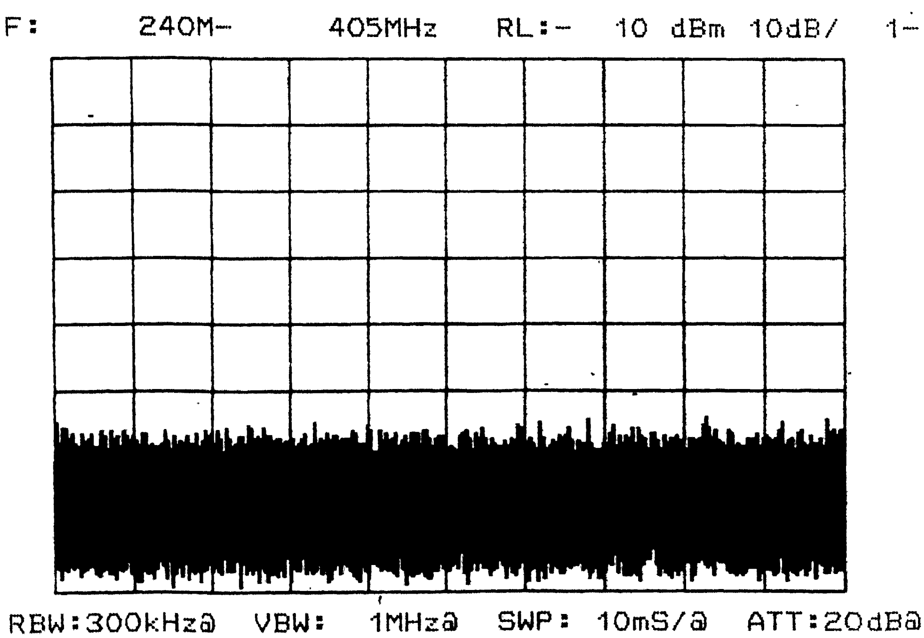


Fig. 4.12 : Frequency Spectrum of EMI due to glow corona at 45 kV, no amplifier in circuit.

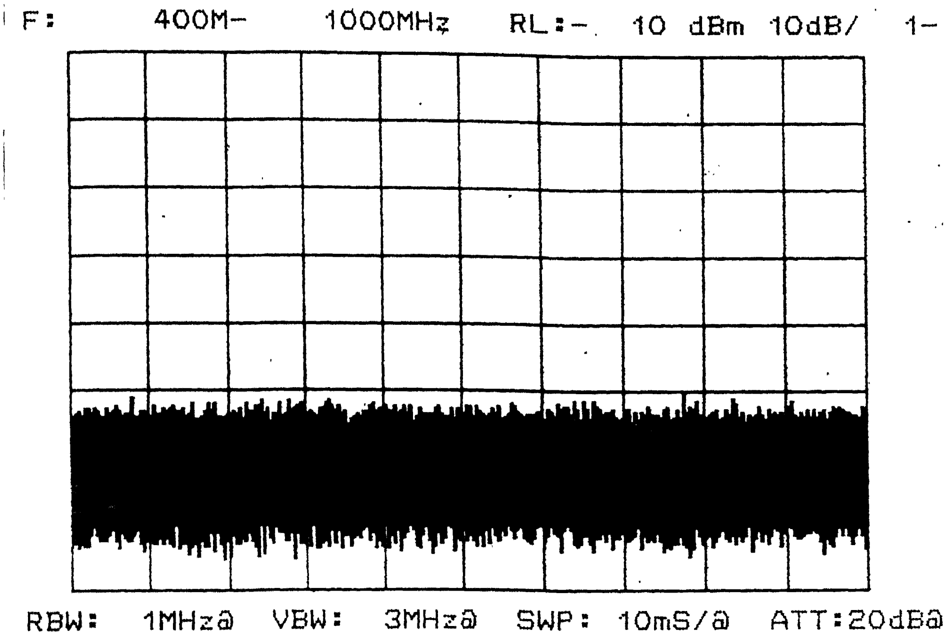


Fig. 4.13 : Frequency spectrum of EMI due to glow corona at 45 kV without amplifiers in circuit.

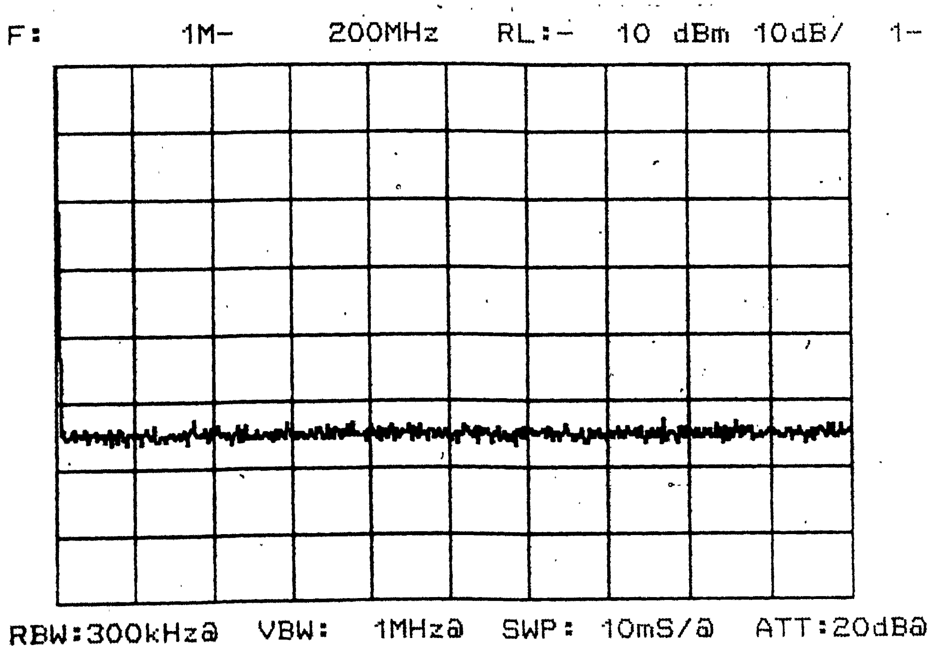


Fig. 4.14 : Frequency spectrum of Noise due to setup without amplifier in circuit, analyzer in maximum hold position.

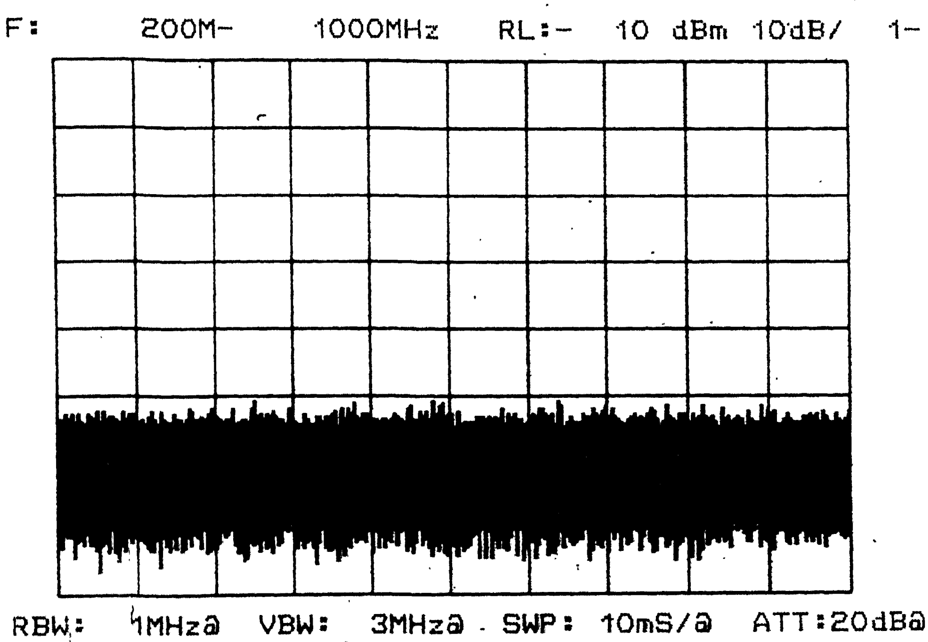


Fig. 4.15 : Frequency spectrum of noise due to setup without amplifier in circuit.

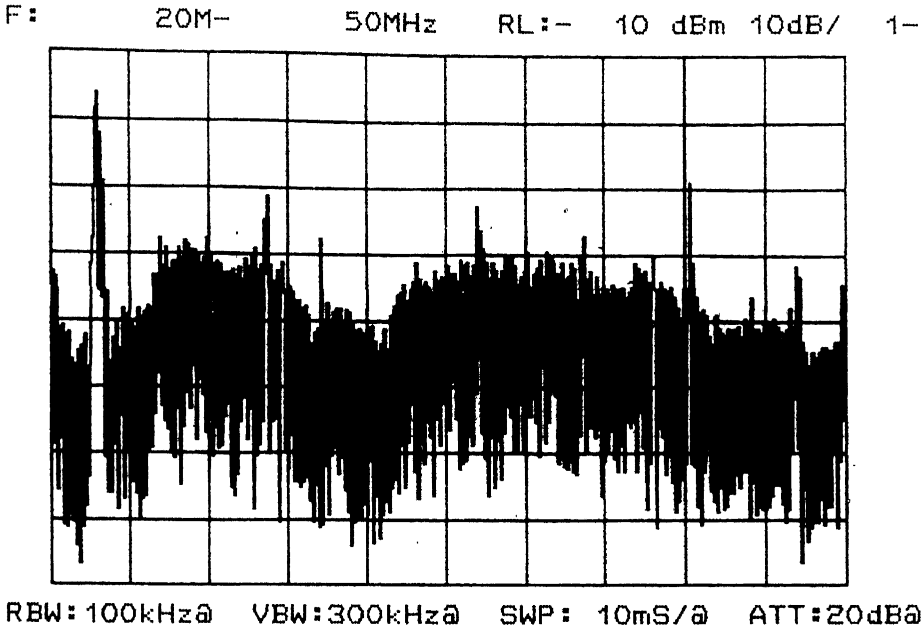


Fig. 4.16 : Frequency spectrum of Noise due to setup with amplifiers in circuit.

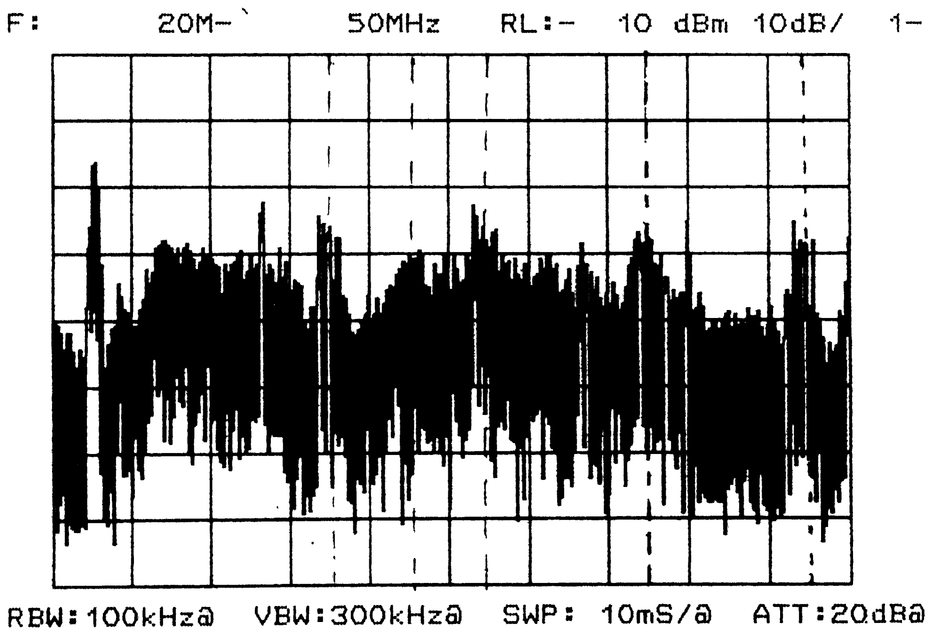


Fig. 4.17 : Frequency Spectrum of EMI due to glow corona, showing its inception at 10 kV, with amplifiers in circuit.

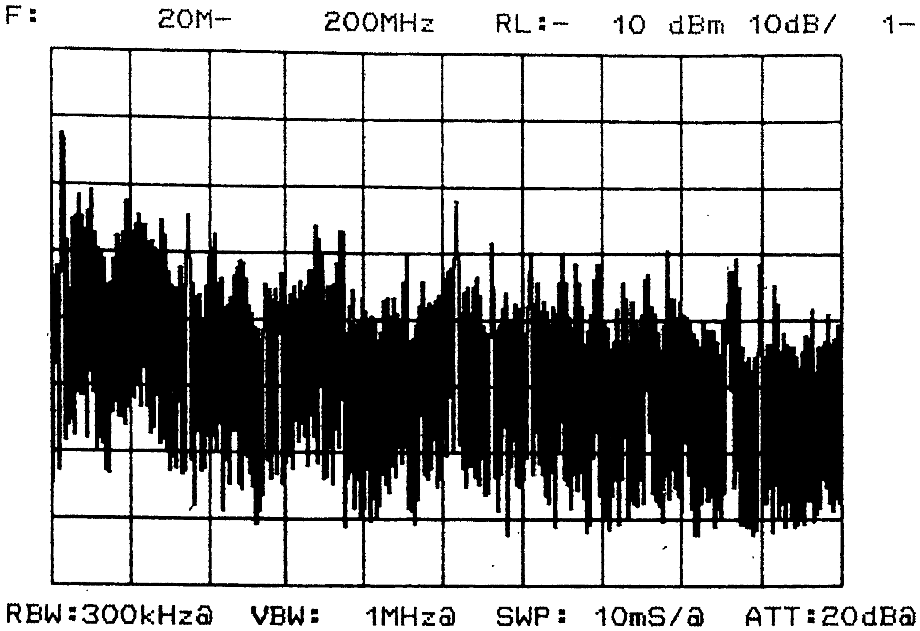


Fig. 4.18 : Frequency spectrum of noise due to setup with amplifiers in circuit.

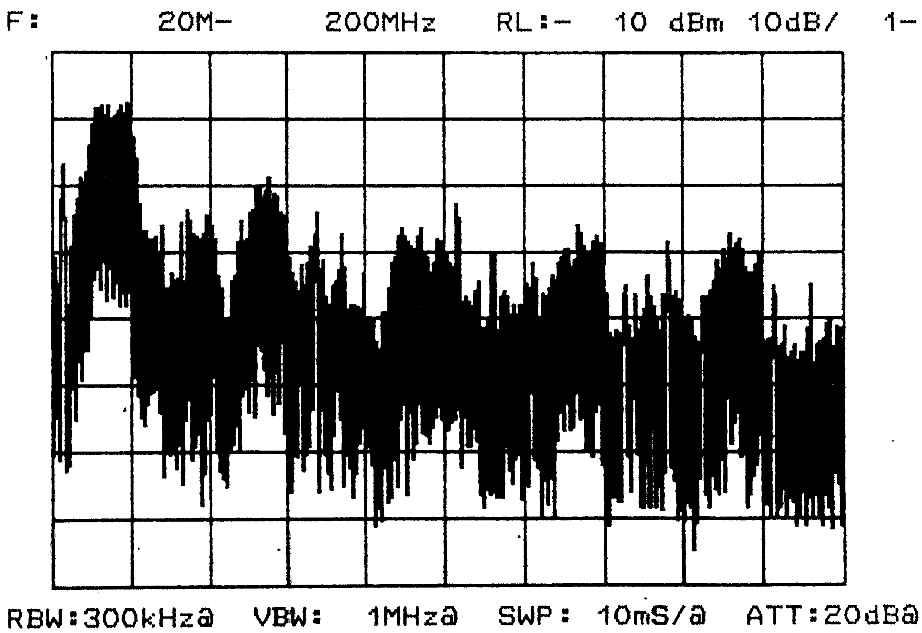


Fig. 4.19 : Frequency spectrum of EMI due to glow corona at 45kV, with amplifiers in circuit.

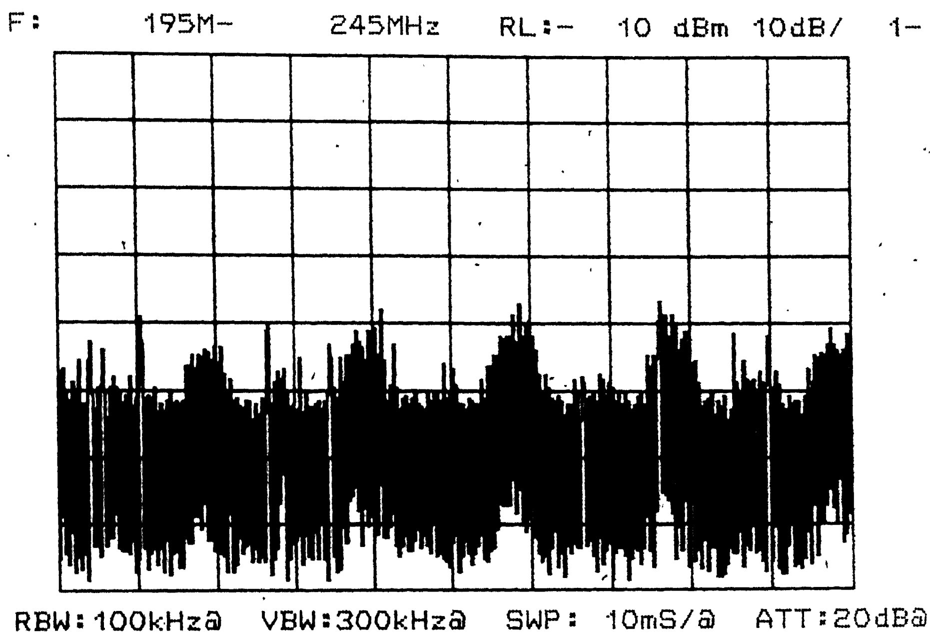


Fig. 4.20 : Frequency spectrum of EMI due to glow corona at 45 kV with amplifiers in circuit.

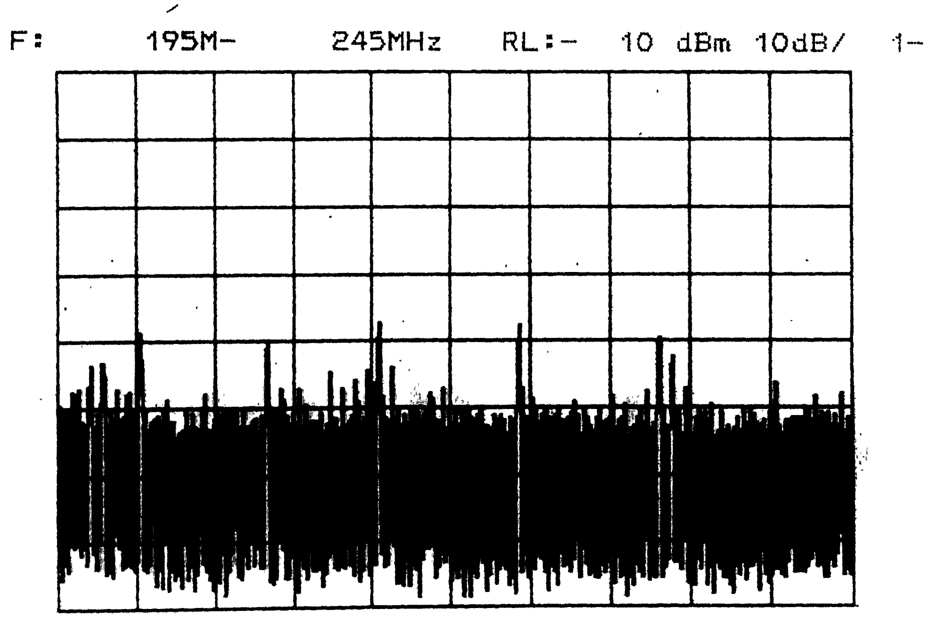


Fig. 4.21: Frequency spectrum of noise due to setup with amplifiers.

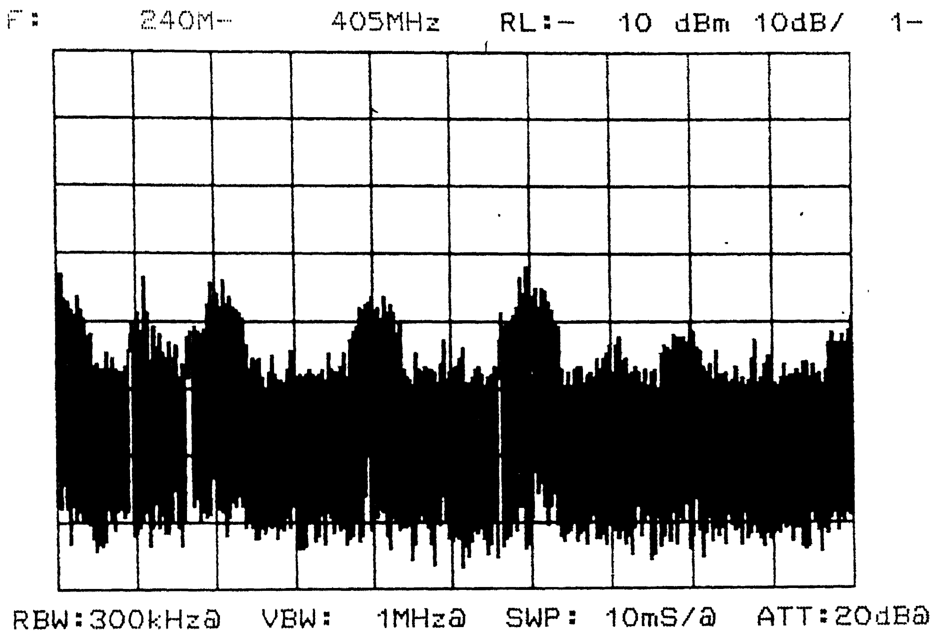


Fig. 4.22 : Frequency spectrum of EMI due to glow corona at 45 kV, with amplifiers in circuit.

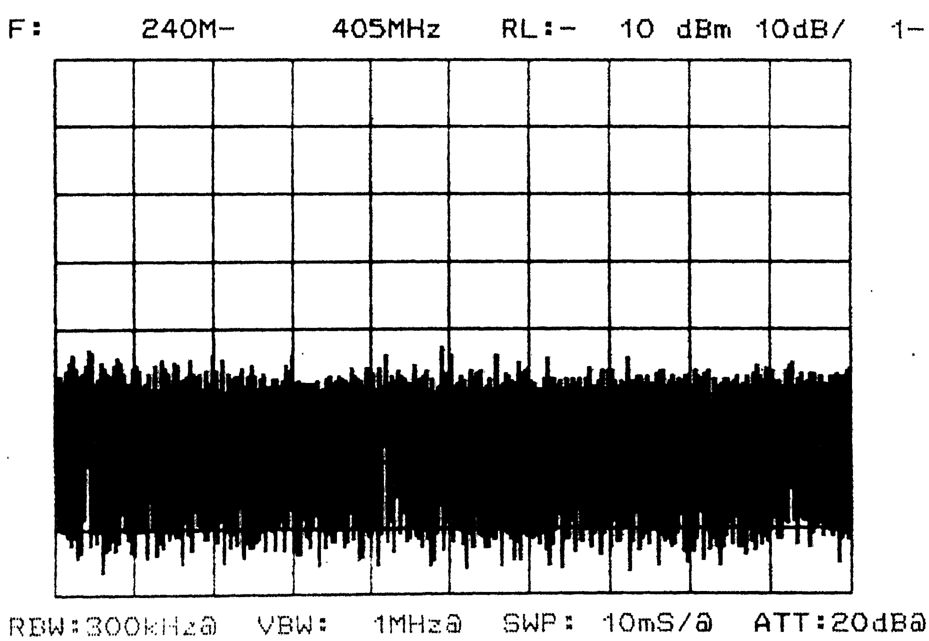


Fig. 4.23 : Frequency spectrum of noise due to setup with amplifiers in circuit.

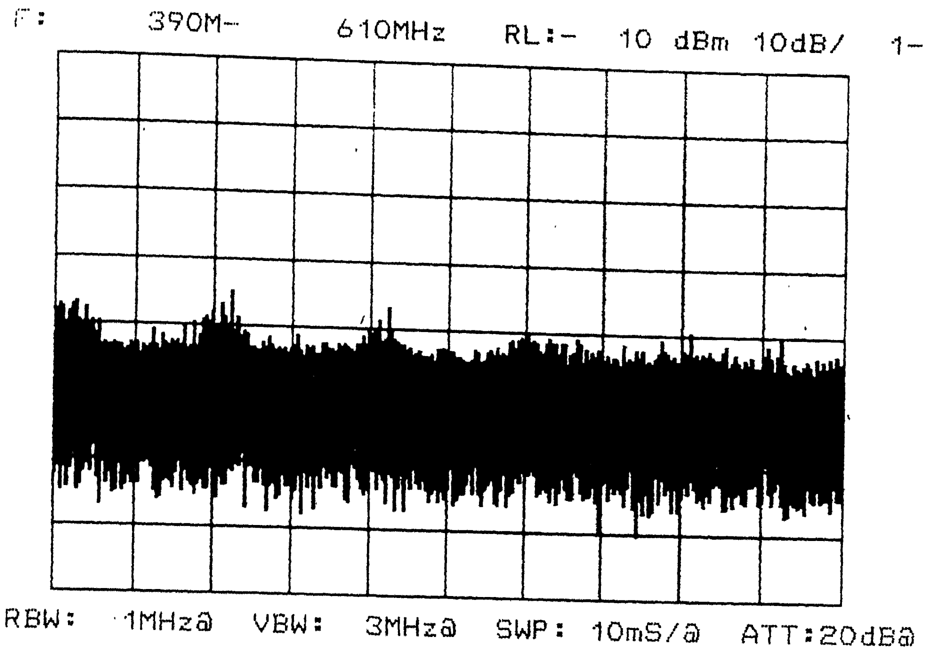


Fig. 4.24 : Frequency spectrum of EMI due to glow corona at 45 kV, with amplifiers in circuit.

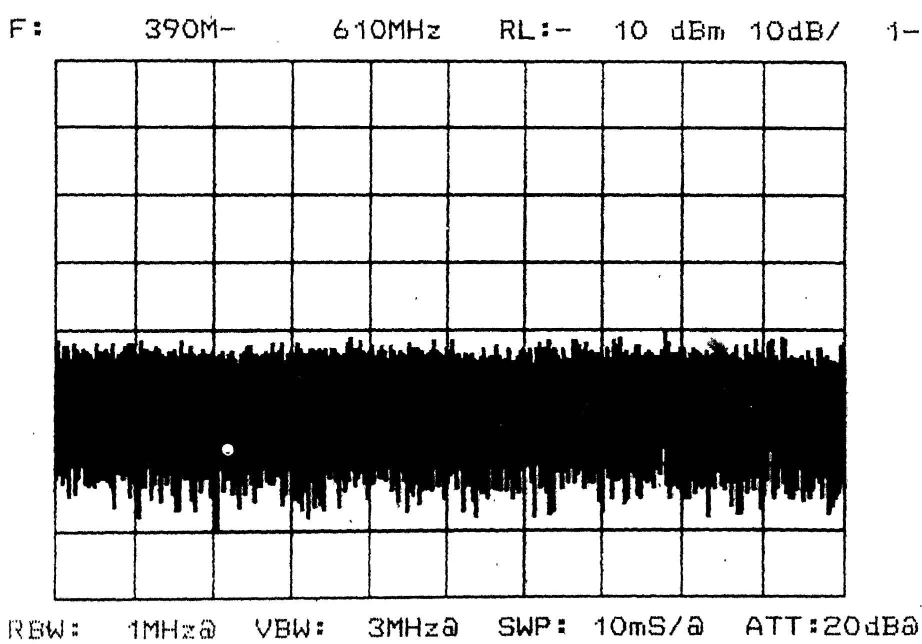


Fig. 4.25: Frequency spectrum of setup noise with amplifiers in circuit.

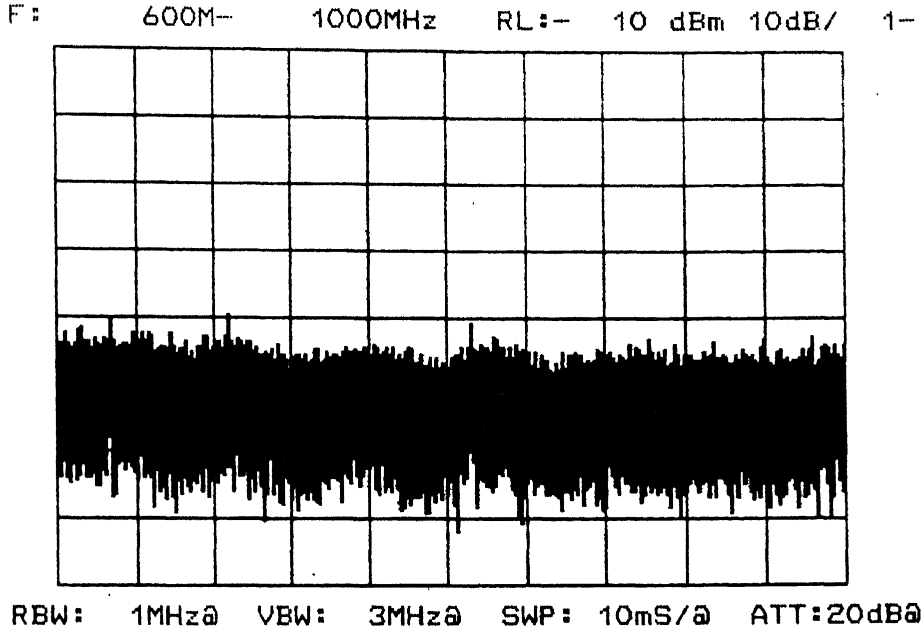


Fig. 4.26 : Frequency spectrum of glow corona at 45 kV with amplifiers in circuit.

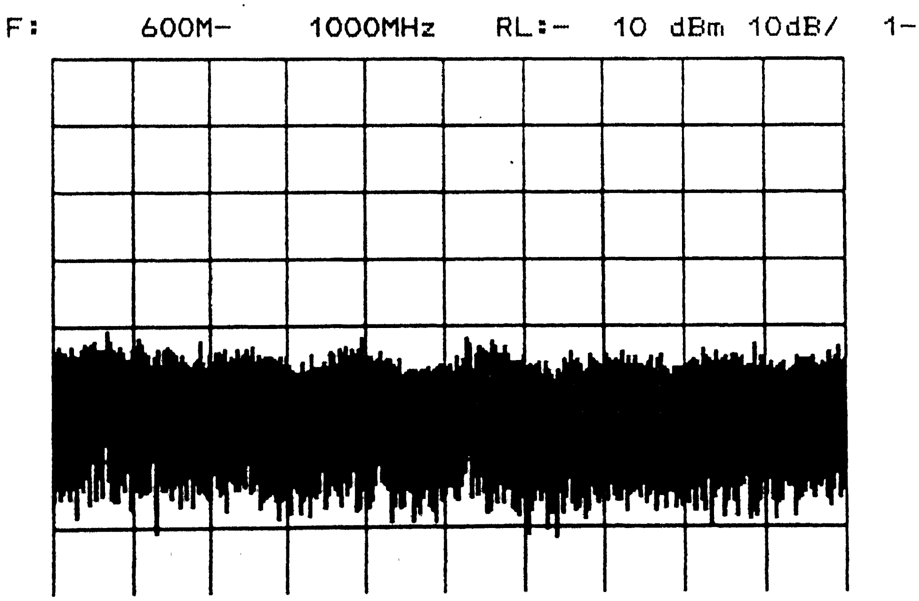


Fig. 4.27 : Frequency spectrum of setup noise with amplifiers in circuit.

5 MEASUREMENT OF EMI DUE TO STREAMER CORONA:

The setup for the measurement of radio noise or EMI due to reamer corona are shown in figures 4.28 and 4.29 for frequency nges from 25 to 200 MHz and 200 to 1000 MHz respectively. The tup for generation of *streamer corona* has been discussed in ction 3.2.2 . Figures 4.30 and 4.32 show the frequency spectrum noise due to *streamer corona* at 45 kV recorded without plifiers. Figure 4.31 and 4.32 show the frequency spectrum of sic noise. On comparing the above set of figures, it is vealed that the noise due to *streamer corona* is not detectable. nce we can conclude that at 45 kV noise due to *streamer corona* less than - 65 dBm / m which is the amplitude of basic noise.

In order to make the noise level due to *streamer corona* pear on CRT of the analyzer, amplifiers i.e. preamplifier and wer amplifier were incorporated in between the antenna and the ectrum analyzer. The details of amplifiers are given in section 33. The output of preamplifier was fed to input of power plifier. Figure 4.34 shows the frequency spectrum of the basic ise for this setup. Figure 4.35 shows the frequency spectrum of ise due to *streamer corona* at 30 kV. On comparing these two gures 4.34 and 4.35, we find that inception of *streamer corona*, rked by dotted line, occurred at 30 kV as seen at 39, 45, and 52 z etc. On raising the voltage from 30 to 45 kV, the level of ise increased considerably. On comparing figure 4.37 with gure 4.36 it is found that noise level due to streamer is ximum in the frequency range from 38 to 43 MHz. The voltage was rther increased to 67 kV. The frequency spectrum (figure 4.38)

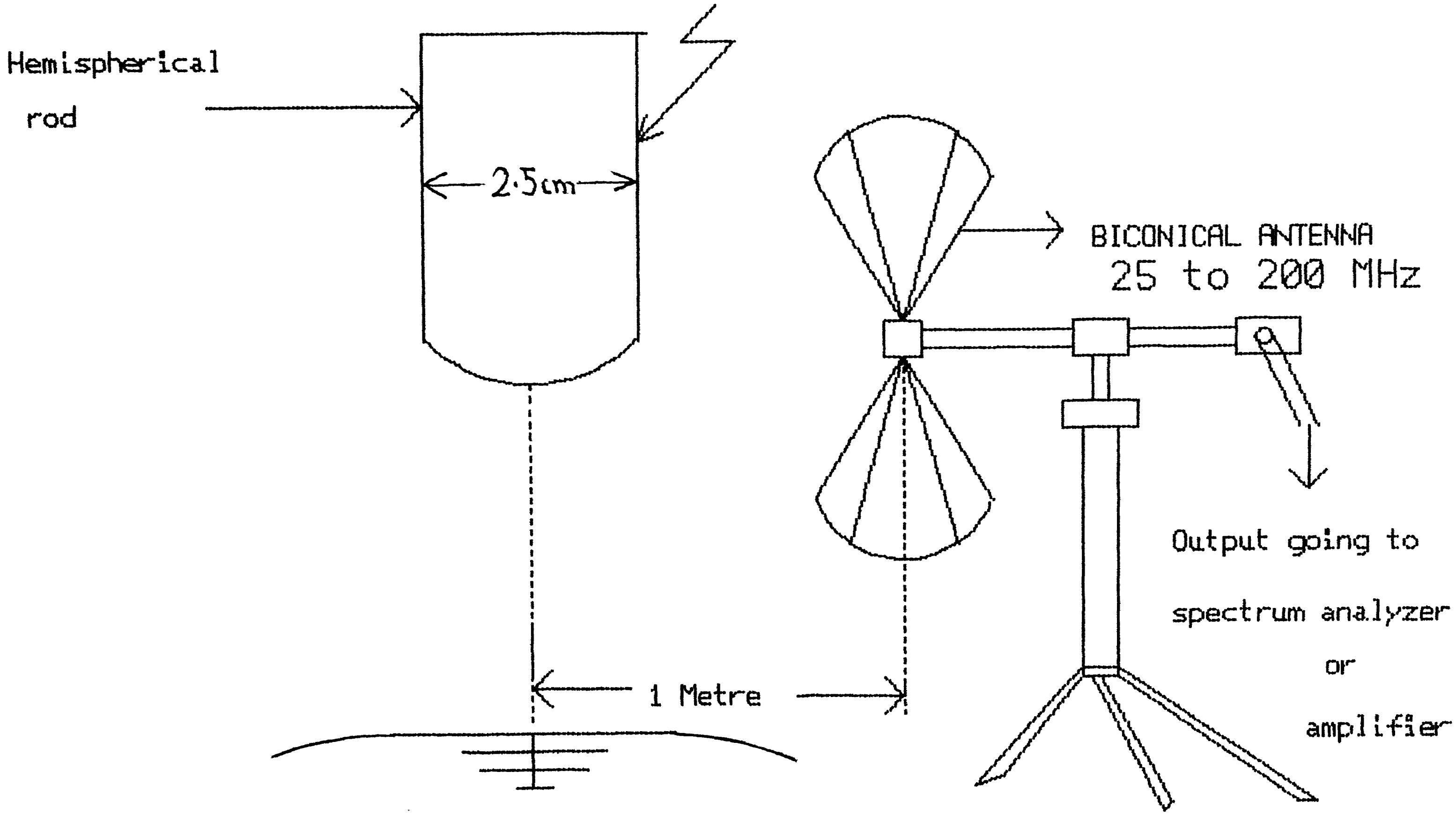


Figure 4.28: Setup for measurement of EMI due to streamer corona in the frequency range of 25 to 200 MHz

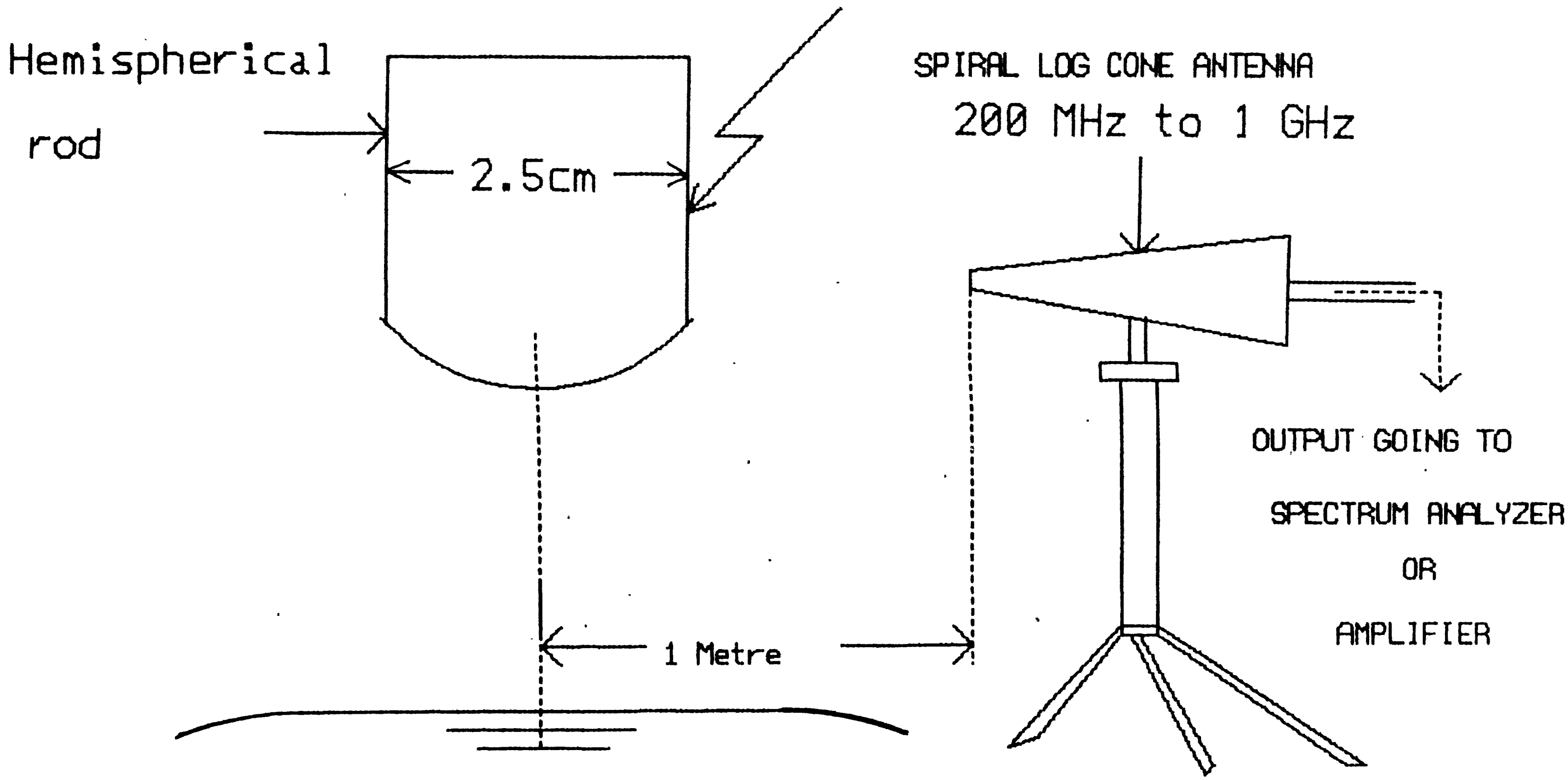


Figure 4.29: Setup for measurement EMI due to streamer corona in the frequency range of 200 MHz to 1 GHz

ecorded at this voltage in the frequency range of 20 to 80 MHz eveals on comparing with figure (4.39) that there was only a arginal increase in level of radio noise is by 5 dBm.

Figure 4.40 shows the frequency spectrum of *streamer corona* t 45 kV in the frequency range of 20 to 200 MHz. On comparing his with figure 4.41 showing the basic noise level it was found hat at 45 kV noise due to streamer was not very high. It was nly about 10 to 5 dBm higher than the basic noise.

As stated earlier Doordarshan video frequency at Kanpur is 75.25 MHz and video bandwidth is 5.0 MHz. But since vestigial ide band technique is used for transmission, the video signal ies in the frequency range of 174 to 180.25 MHz. In order to ind whether noise due to *streamer corona* was present in this requency range or not, a comparison is needed to be made between igures 4.40 and 4.41, It reveals that noise due to *streamer orona* is negligible at 45 kV beyond 160 MHz. This fact is also erived after comparing figures 4.42, 4.44, and 4.46 which are requency spectrum recordings of *streamer corona* in the frequency ange of 195 to 1000 MHz at 45 kV. Figures 4.43, 4.45 and 4.47 how noise levels of antenna, amplifier and spectrum analyzer for omparison.

Pulses occurring due to *streamer corona* are also broad band ignals . In order to calculate spectral intensity, for example or amplitude equal to - 28 dBm at 29 MHz read from the figure .36, following the same procedure as given at the end of section .4, it is equal to 49.28 dB μV / m MHz.

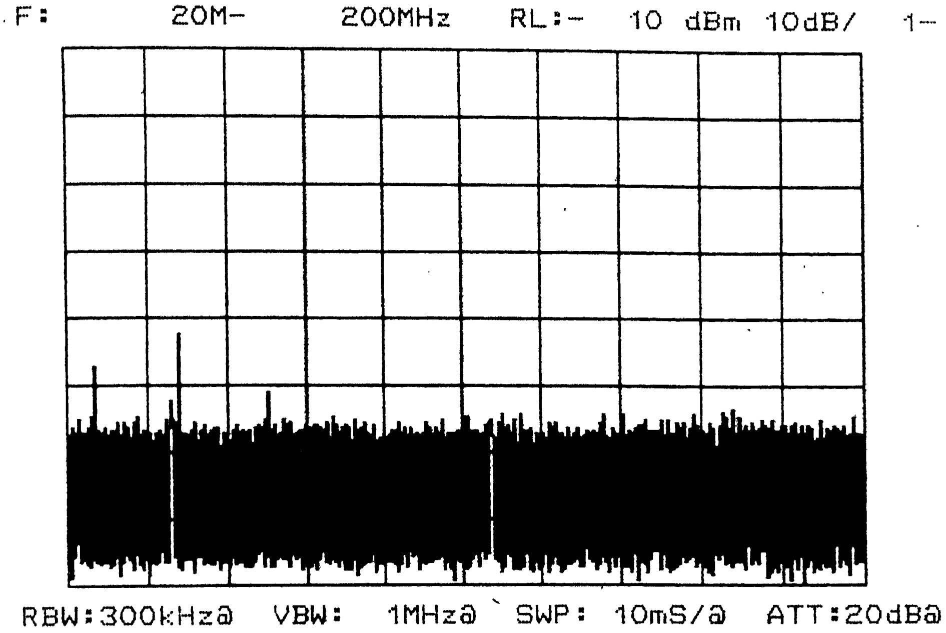


Fig. 4.30 : Frequency spectrum of EMI due to streamer corona.

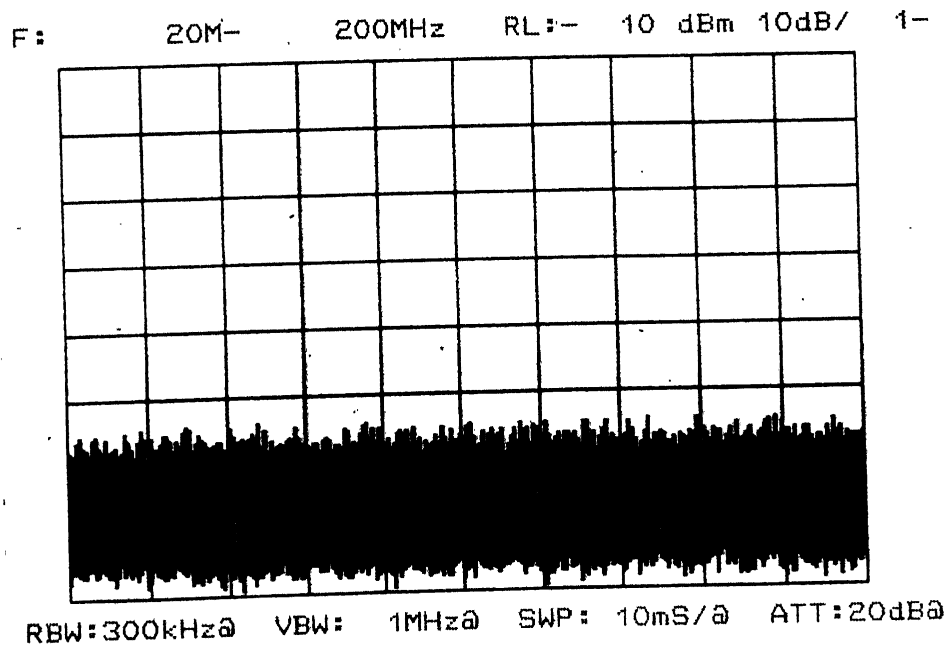


Fig. 4.31 : Frequency spectrum of noise due to setup without amplifier in circuit.

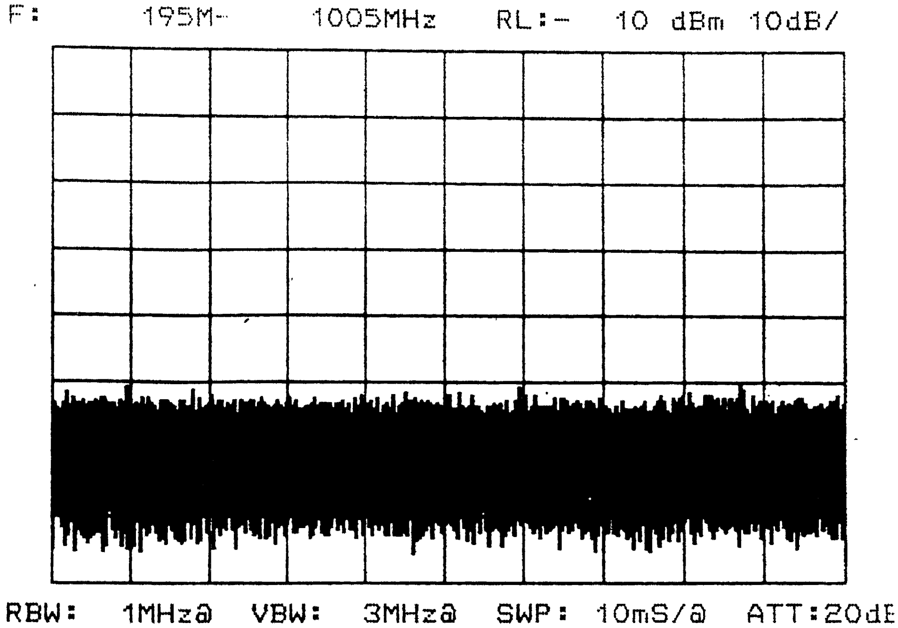


Fig. 4.32 : Frequency spectrum of EMI due to streamer corona at 45 kV, without amplifier in circuit.

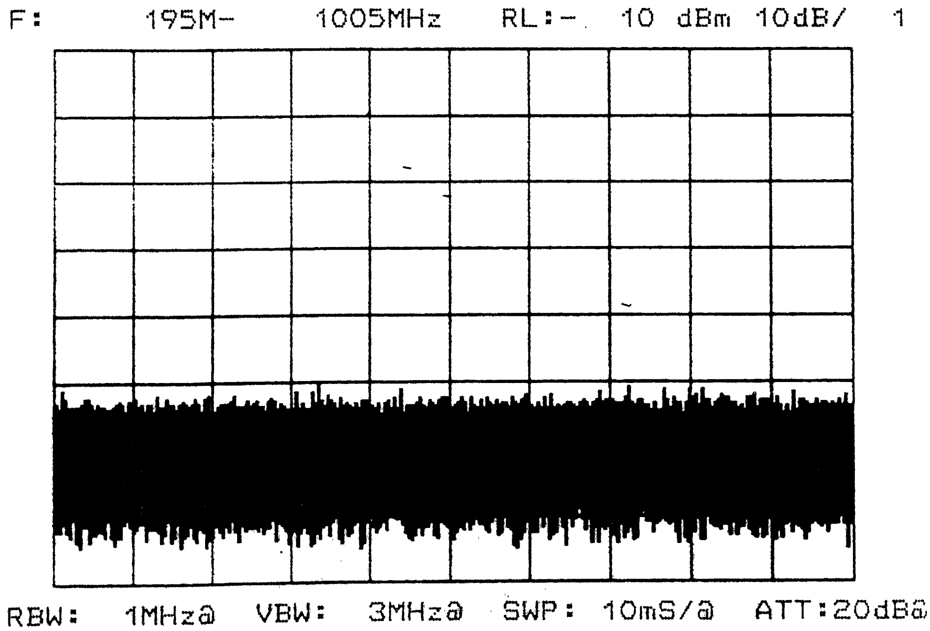


Fig. 4.33 : Frequency spectrum of noise due to setup, no amplifier in circuit.

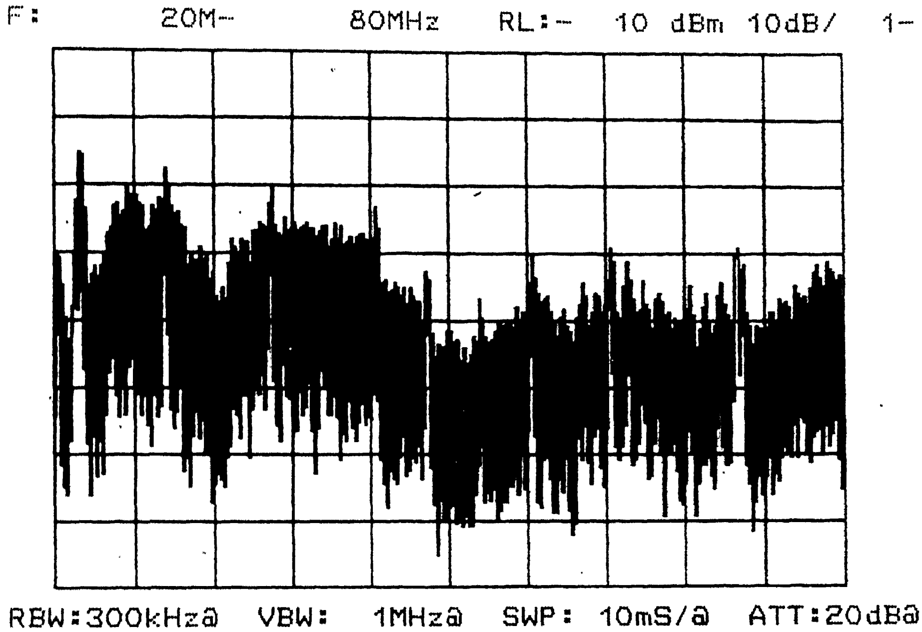


Fig. 4.34 : Frequency spectrum of noise of setup with amplifiers in circuit.

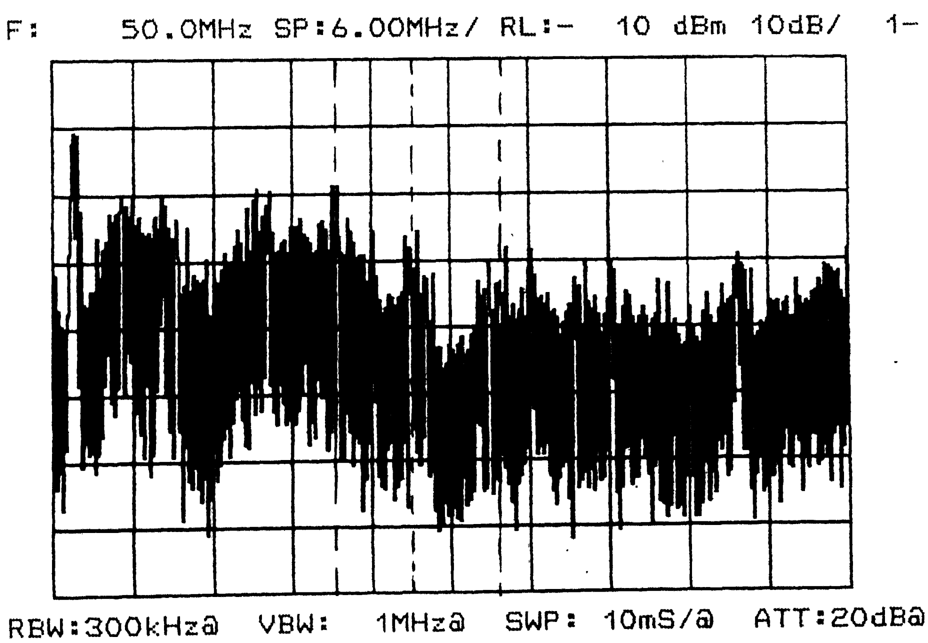


Fig. 4.35 : Frequency spectrum of EMI due to streamer corona showing its inception with amplifiers in circuit.

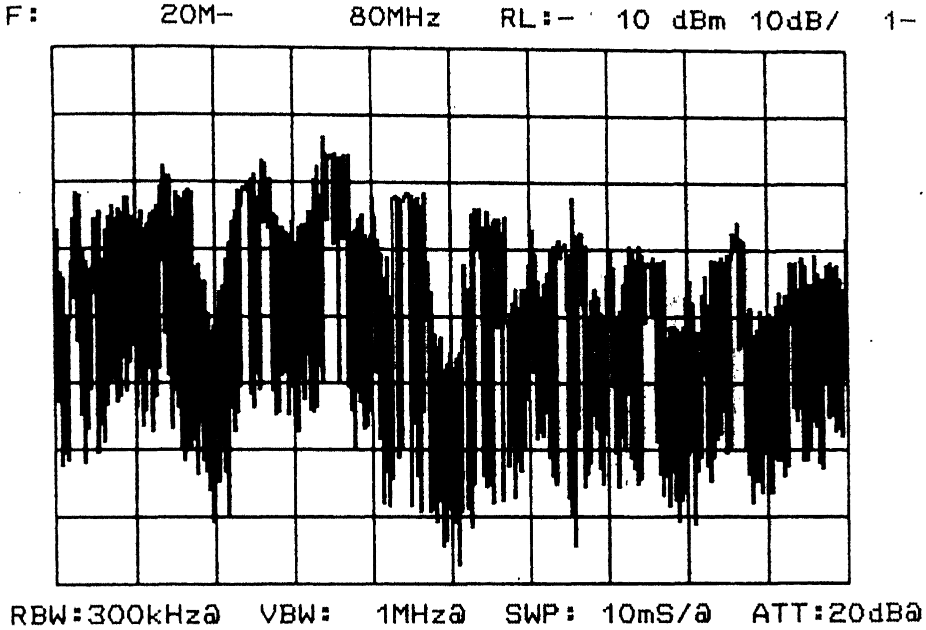


Fig. 4.36 : Frequency spectrum of EMI due to streamer corona at 45 kV, with amplifiers.

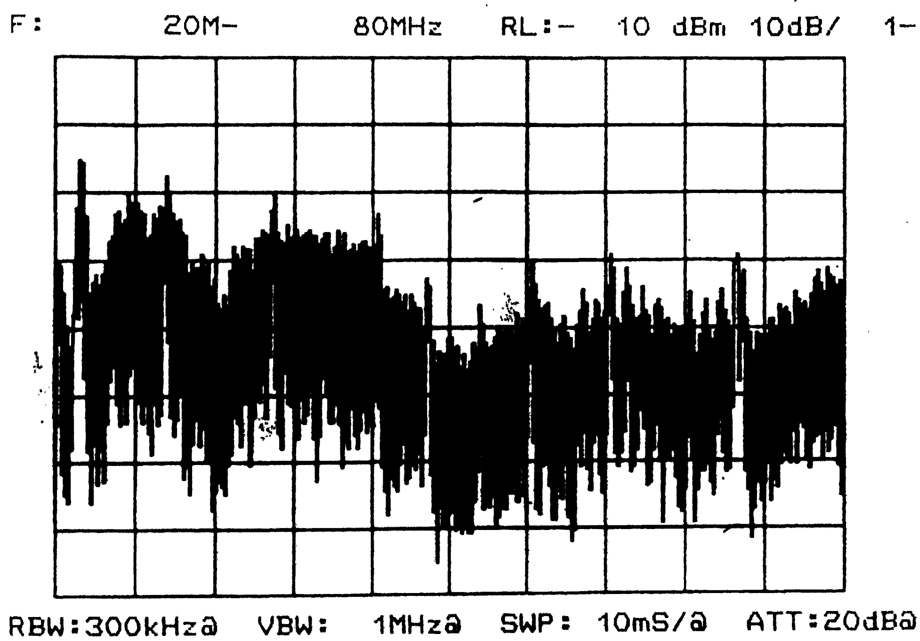


Fig. 4.37 : Frequency spectrum of noise due to setup, with amplifiers in circuit.

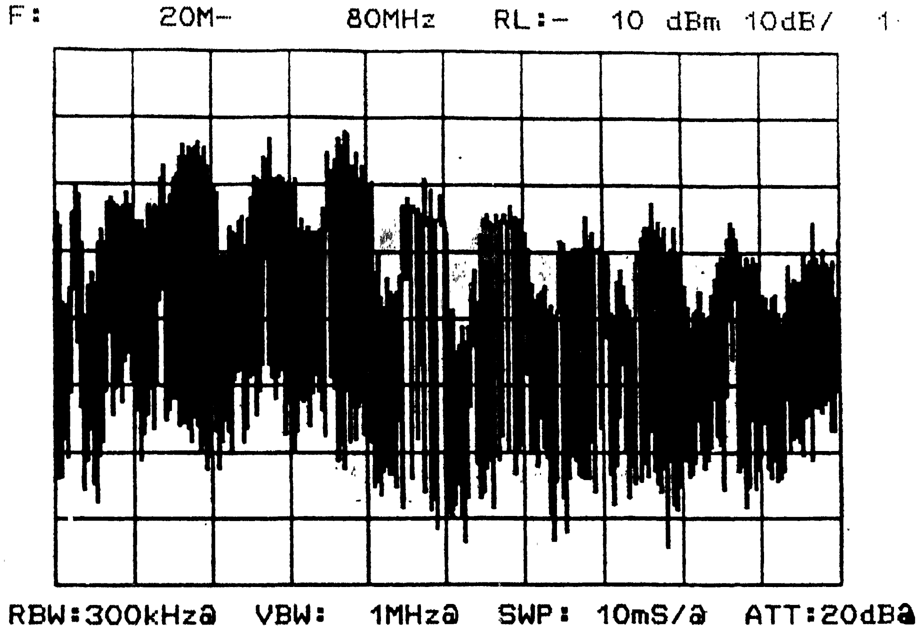


Fig. 4.38 : Frequency spectrum of EMI due to streamer corona at 67 kV, with amplifiers in circuit.

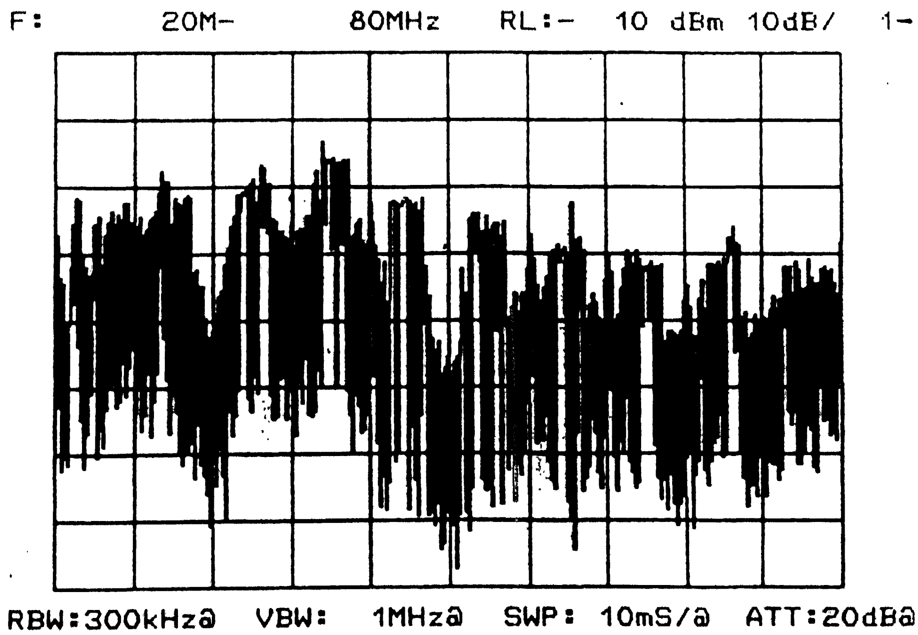


Fig. 4.39 : Frequency spectrum of EMI due to streamer corona at 45 kV, with amplifiers in circuit.

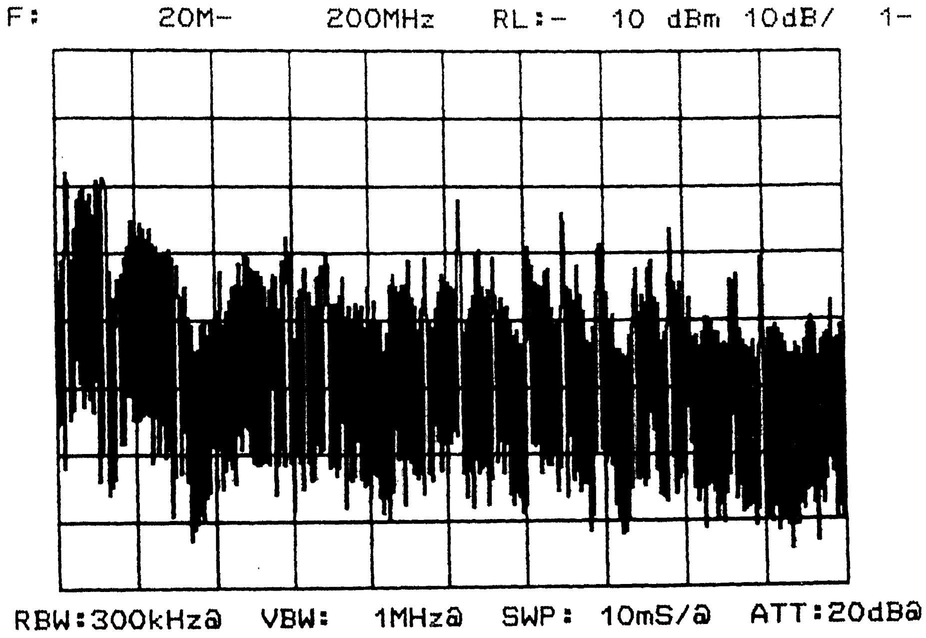


Fig. 4.40 : Frequency spectrum of EMI due to streamer corona, with amplifiers in circuit.

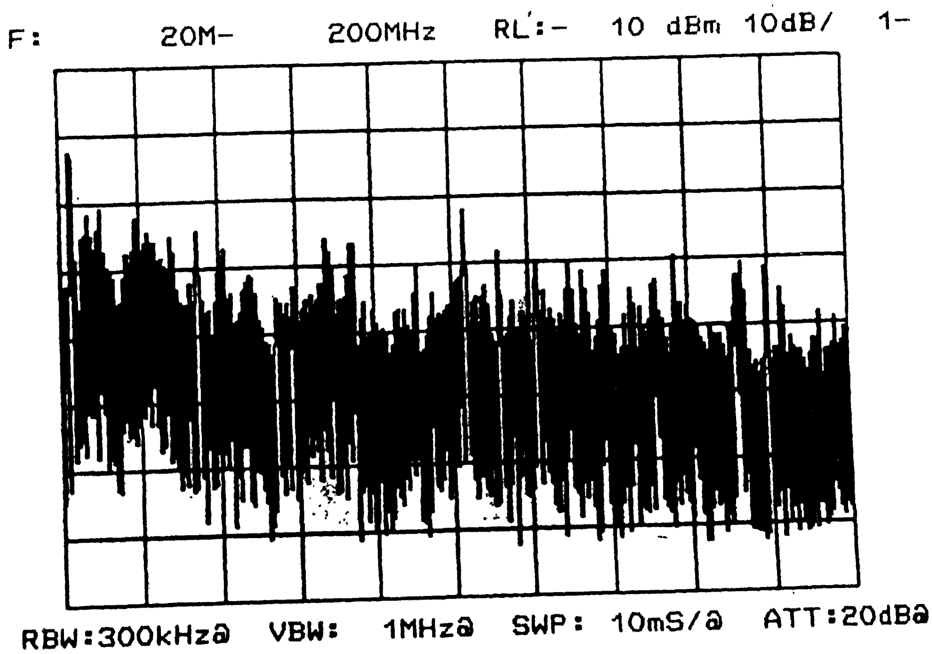


Fig. 4.41 : Frequency spectrum of noise due to setup with amplifiers in circuit.

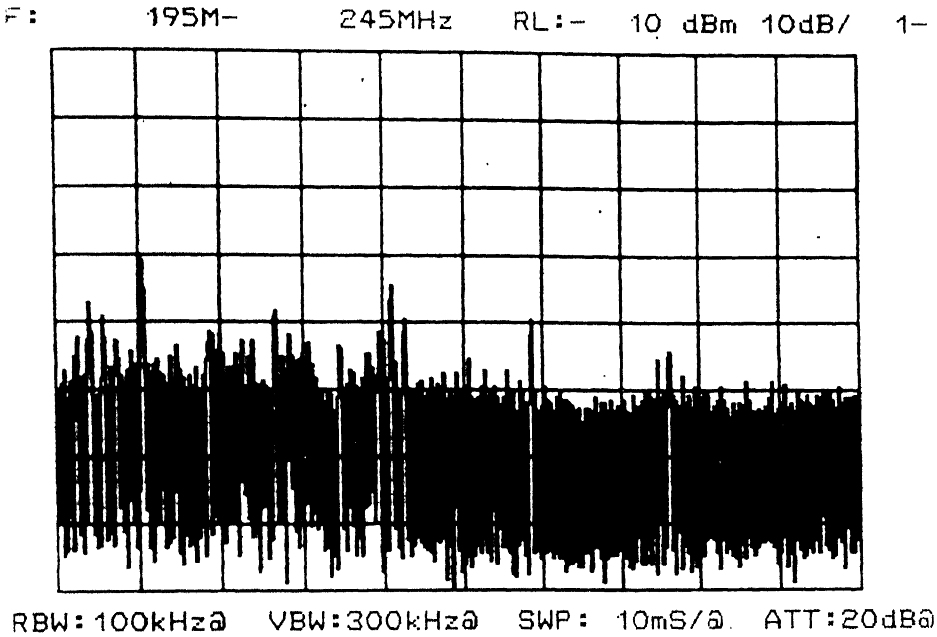


Fig. 4.42 : Frequency spectrum of EMI due to streamer corona at 45 kV, with amplifiers in circuit.

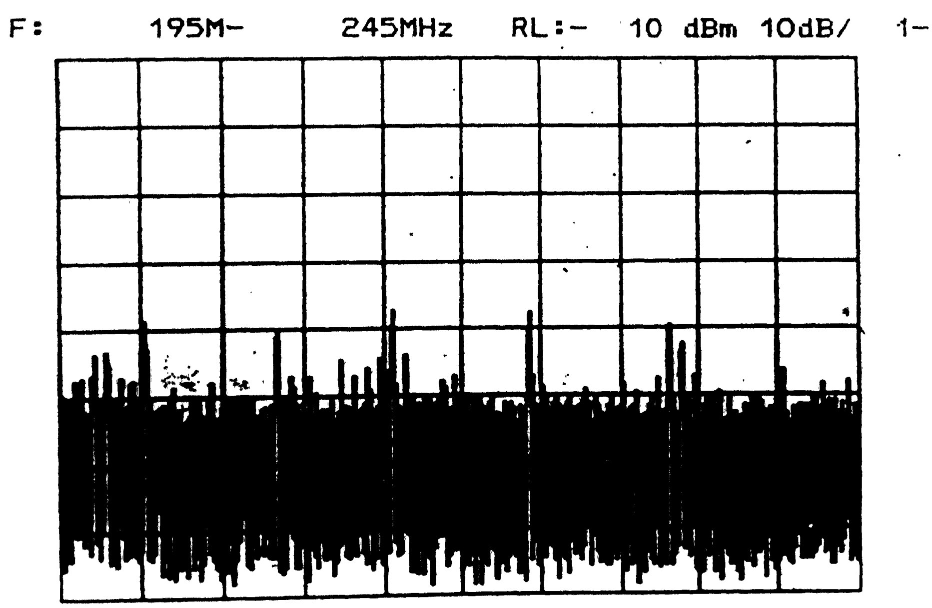


Fig. 4.43 : Frequency spectrum of noise due to setup, with amplifiers in circuit.

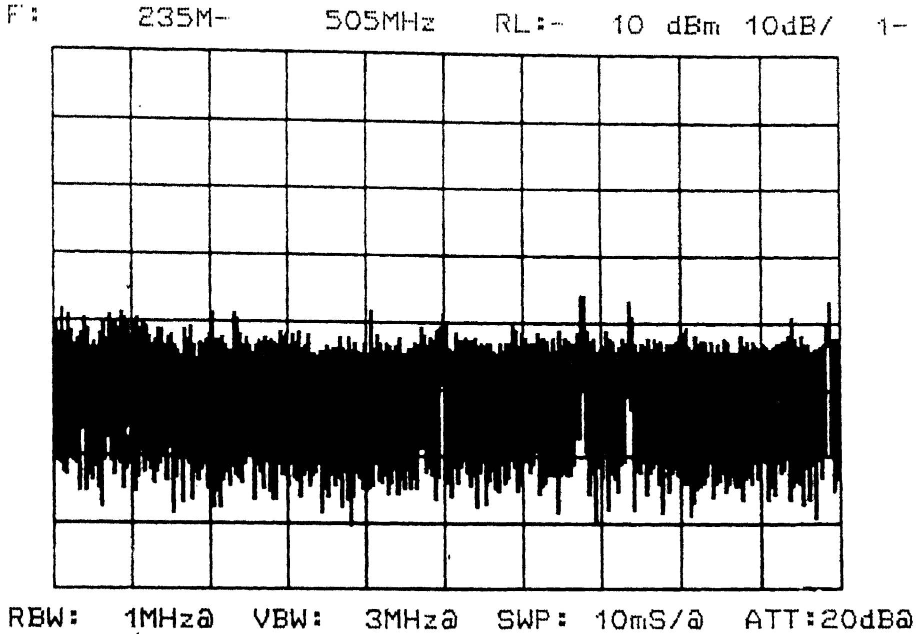


Fig.4.44 : Frequency spectrum of EMI due to Streamer corona at 45 kV with amplifier in circuit.

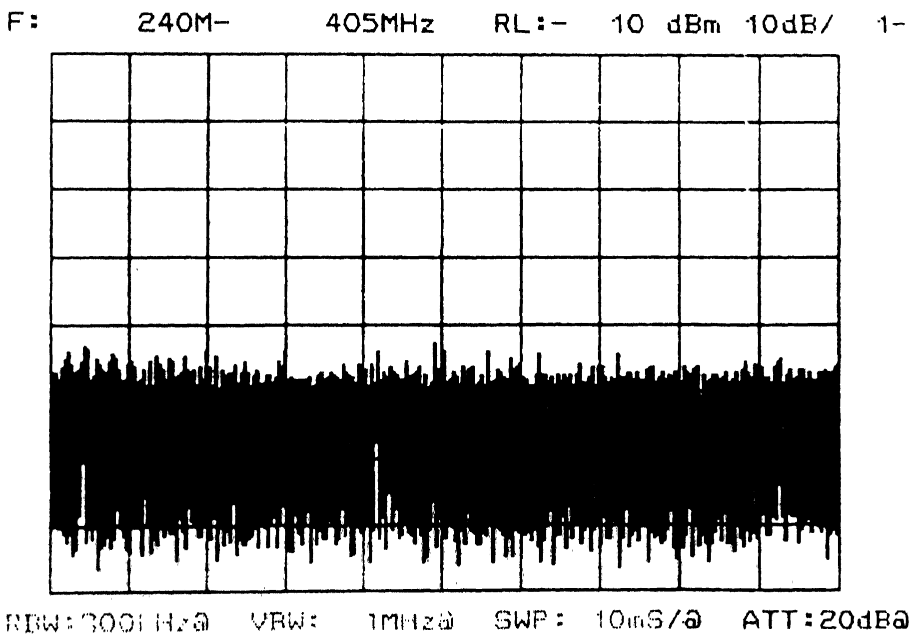


Fig. 4.45 : Frequency spectrum of noise due to setup with amplifiers in circuit.

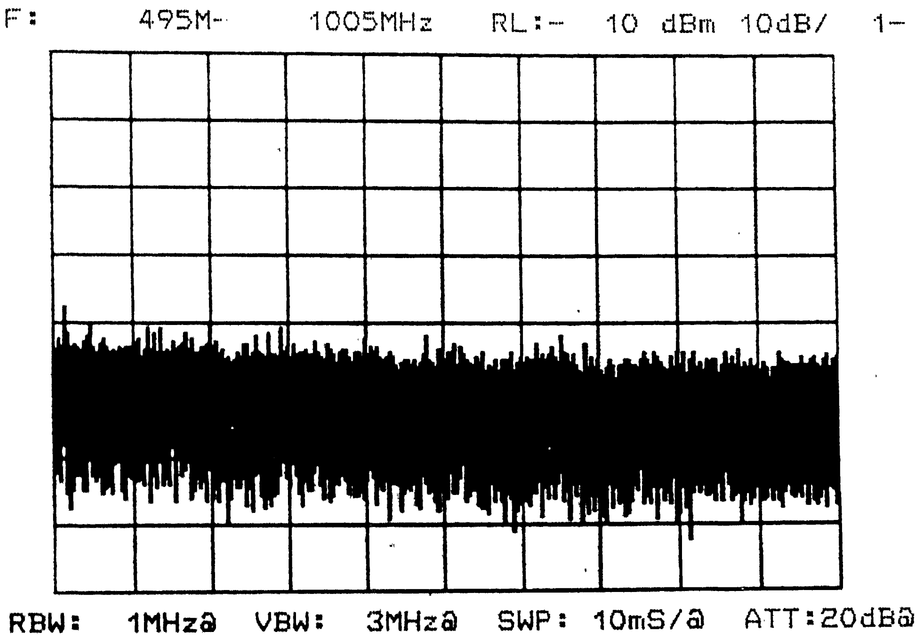


Fig. 4.46: Frequency spectrum of streamer corona at 45 kV, with amplifiers in circuit.

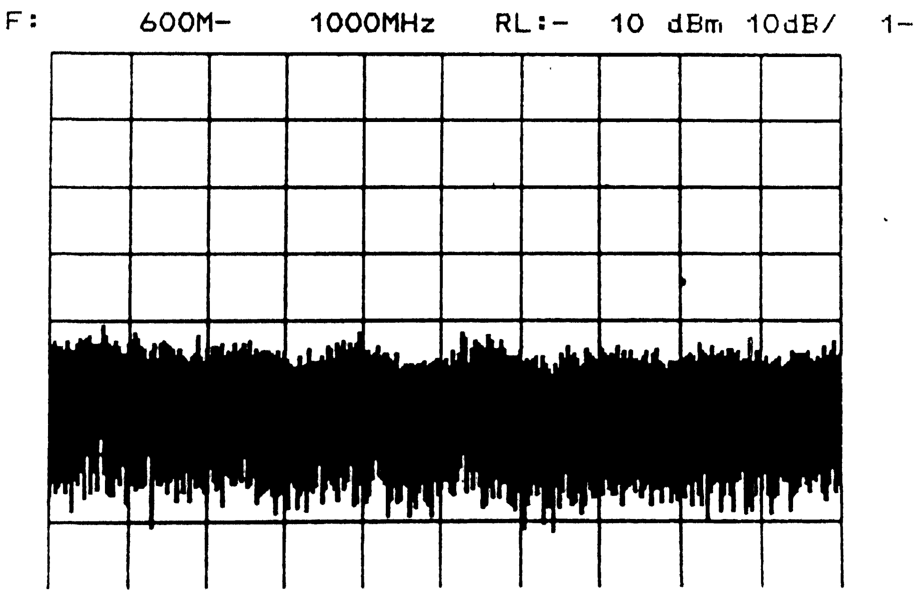


Fig. 4.47 : Frequency spectrum of noise due to setup, with amplifiers in circuit.

.6 MEASUREMENT OF EMI DUE TO LEADER CORONA:

The setup for the measurement of radio noise due to leader ɔrona are shown in figures 4.48 and 4.49 in the frequency range f 25 to 200MHz and 200 to 1000 MHz respectively. The electrode etup for the generation of *leader corona* has been discussed in ection 3.2.3. Radio noise due to *leader corona* are also broad and signals . Their amplitude in terms of spectral intensity is valuated towards the end of this section. Discharges occurring uring *leader corona* are very powerful in the sense that they are roduced due to vigorous ionization resulting in very bright ischarge channels, accompanied with strong audible noise. This is he reason that the radio noise due to *leader corona* was etectable on the analyzer without boosting the signal level with he help of preamplifier. However their intensity dropped above 5 MHz and therefore, a preamplifier was inserted in order to ncrease the sensitivity of the analyzer mainly above this requency.

Figure 4.50 shows the frequency spectrum of the basic noise f the setup in the frequency range of 10 to 50 MHz. Figure 4.51 hows the frequency spectrum of noise produced due to *leader orona* at 4 kV. On comparing the two figures 4.50 and 4.51 it is evealed that the inception of *leader corona* took place at this oltage which is marked as dotted line showing its amplitude to be 59.8 dBm at 27.20 MHz. Figure 4.52 shows frequency of noise due o *leader corona* at 17 kV in the frequency range of 1 to 100 MHz hereas figure 4.53 shows the basic noise of the setup. Comparing hese two figures it is clear that the noise due to *leader corona*

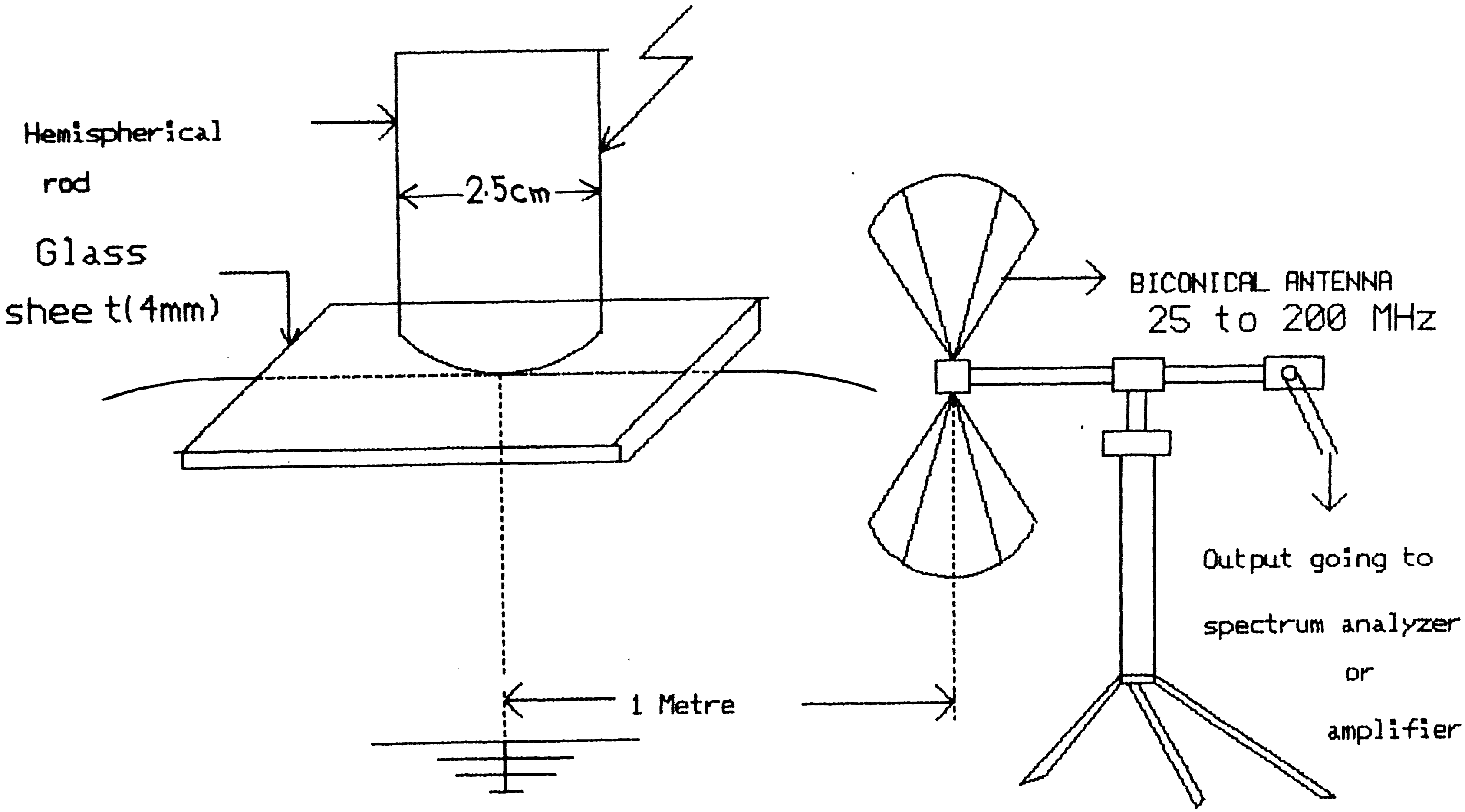


Figure 4.48: Setup for measurement of EMI due to leader corona in the frequency range of 25 to 200 MHz

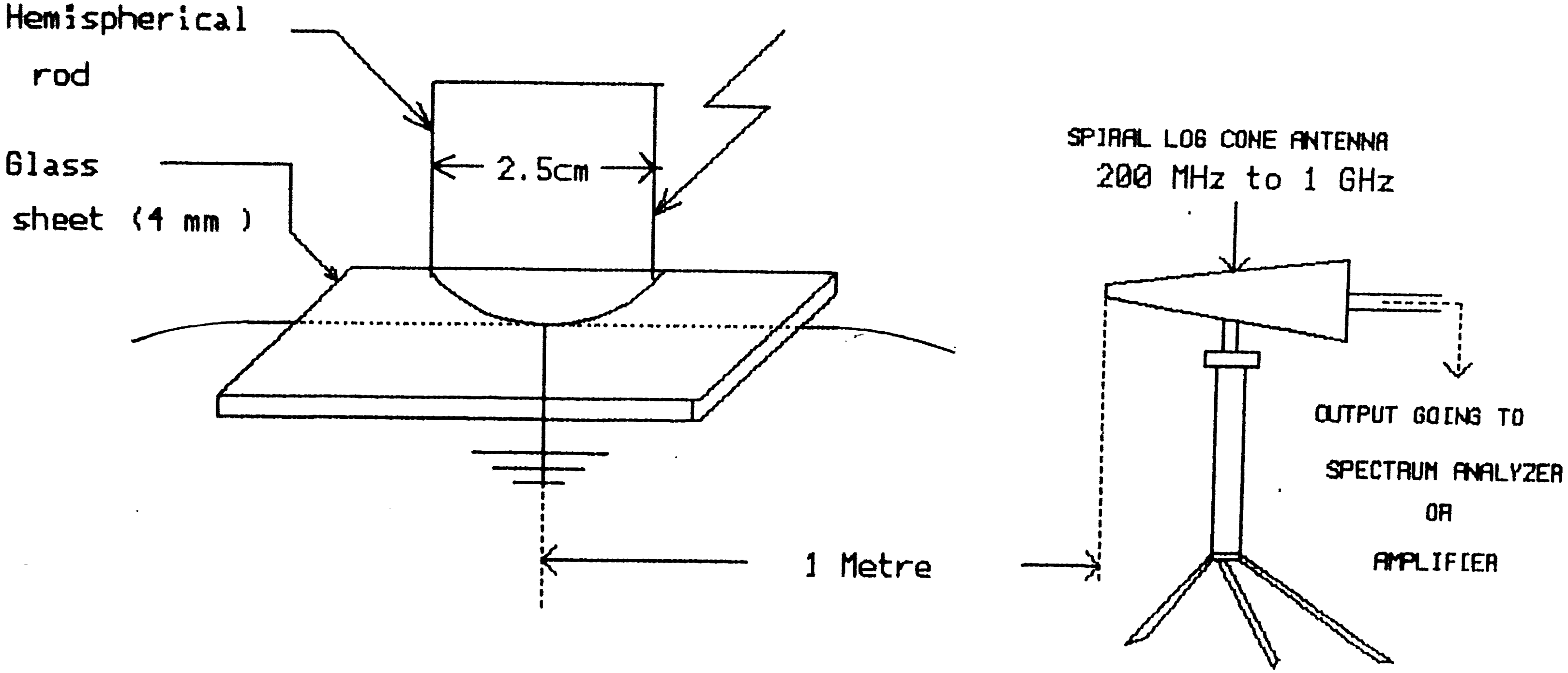


Figure 4.49: Setup for measurement of EMI due leader corona in the frequency range 200 MHz to 1 GHz

is present throughout the frequency range from 1 to 100 MHz. Biconical antenna used for this measurement attenuates frequencies below 25 MHz but the *leader corona* discharges are so strong that they are well detectable even below 25 MHz. Leader corona caused intensive interference to the short wave and medium wave radio frequencies as detected by radio receiver. Figure 4.54 shows noise due to *leader corona* at 17 kV in the frequency range of 95 to 200 MHz. In this figure noise due to *leader corona* is not detectable beyond 152 MHz. Hence a preamplifier was used once again. Figure 4.55 shows noise due to preamplifier, antenna and spectrum analyzer and figure 4.56 the noise due to *leader corona*. On comparing these two figures it is found that noise due to *leader corona* is present through out the frequency range from 95 to 200 MHz. Like in case of *glow corona*, the noise due to *leader corona* was present at 17 kV itself in the frequency range of 174 to 180.25 MHz, which is KANPUR Doordarshan video signal range. Level of noise present in the frequency range was about - 45 dBm. It strongly interferes the TV signals as demonstrated later on. Figures 4.57, 4.59, 4.61, 4.63 show the frequency spectrum of noise due to antenna, amplifier and spectrum analyzer whereas figures 4.58, 4.60 4.62 and 4.64 show the noise due to *leader corona* at 17 kV at different frequency ranges. On comparing these figures it is found that noise due to *leader corona* is not present at some intermittent frequencies in the range of 400 to 1000 MHz. All the figures showing frequency spectrum of *leader corona* reveal that noise due to *leader corona* is present upto 1000 MHz. The noise is actually present even beyond 1000 MHz due to *leader* *corona* but since the antenna bandwidth for satisfactory performance was from 200 to 1000 MHz only, the measurements at higher frequencies could not be relied upon.

Pulses occurring due to *leader corona* are also broad band signal. In order to calculate spectral intensity, for amplitude equal to - 13 dBm at 29 MHz read from figure 4.52, following the same procedure as given at the end of section 4.4, it works out to be 98.78 dB μV / m MHz.

4.7 DEMONSTRATION OF THE EFFECTS OF VARIOUS TYPES OF CORONAS ON THE PERFORMANCE OF TELEVISION:

A colour television, whose details are given in section 3.3.5, was used to demonstrate the effects of various types of coronas on the picture. Two Yagi antennae containing five elements were used simultaneously. One to receive TV transmission signals and the other for the corona noise. The later antenna was placed at a distance of one metre from the corona source. Figures 4.65 and 4.66 show the effects of noise due to *glow corona* at 45 kV. It appears in the form of a band of small but comparatively less bright spots. Spectrum analyzer figure 4.19 also showed that noise due to *glow corona* was present in TV video signal frequency range at 45 kV.

Figure 4.67 and 4.68 shows the effect of *streamer corona* on TV picture. In this case noise due to *streamer corona* was detectable only above 45 kV and these photographs were taken at 85 kV. Noise due to *streamer corona* is present on the TV picture in the form of comparitively less numbers of scattered bright spots.

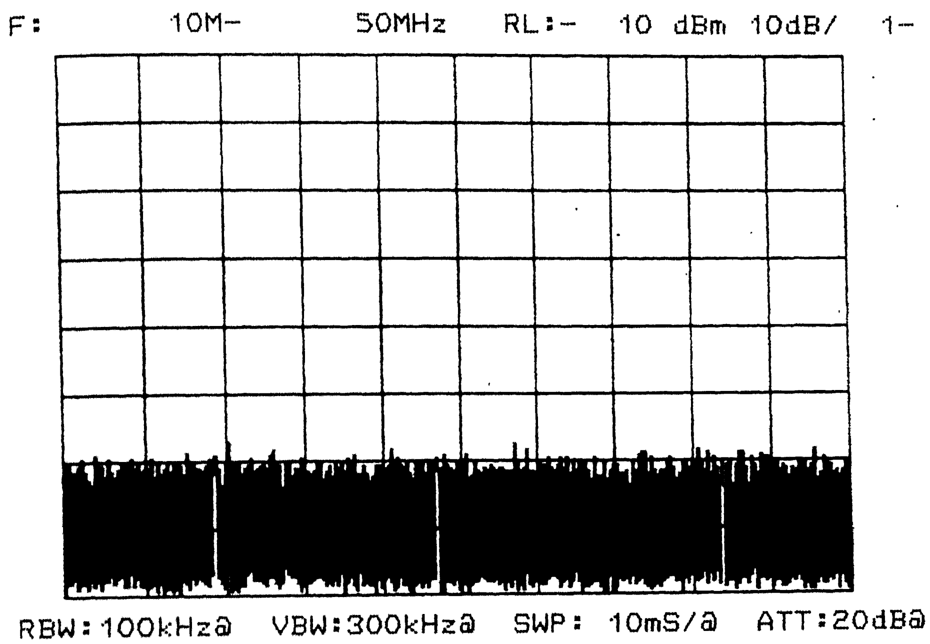


Fig. 4.50 : Frequency spectrum of noise due to setup without amplifier in circuit.

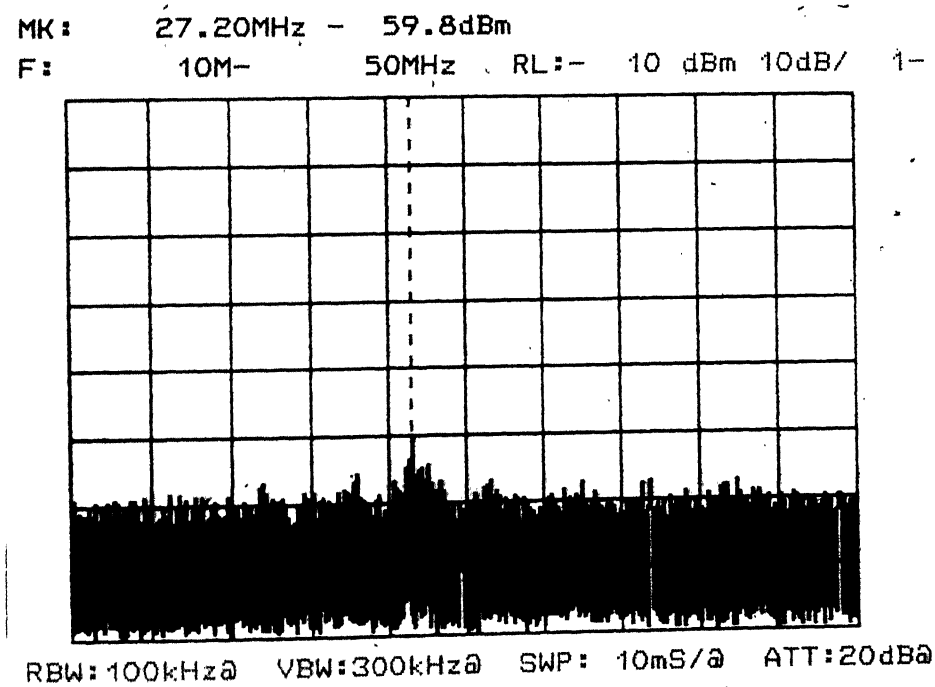


Fig. 4.51 : Frequency spectrum of EMI due to leader corona at 4 kV showing its inception, no amplifier in circuit.

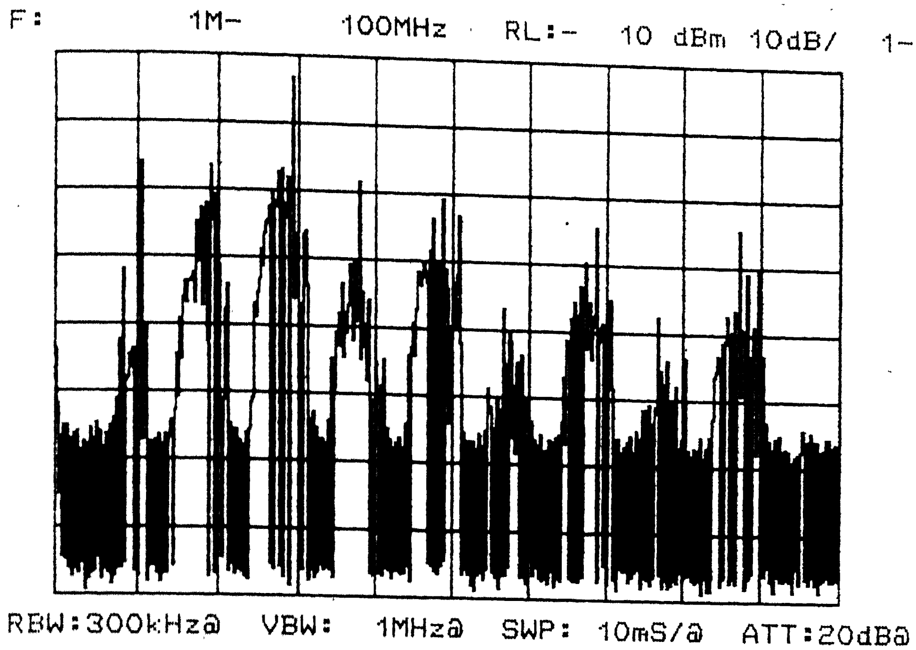


Fig. 4.52 : Frequency spectra of EMI due to leader corona at 17 kV, no preamplifier in circuit.

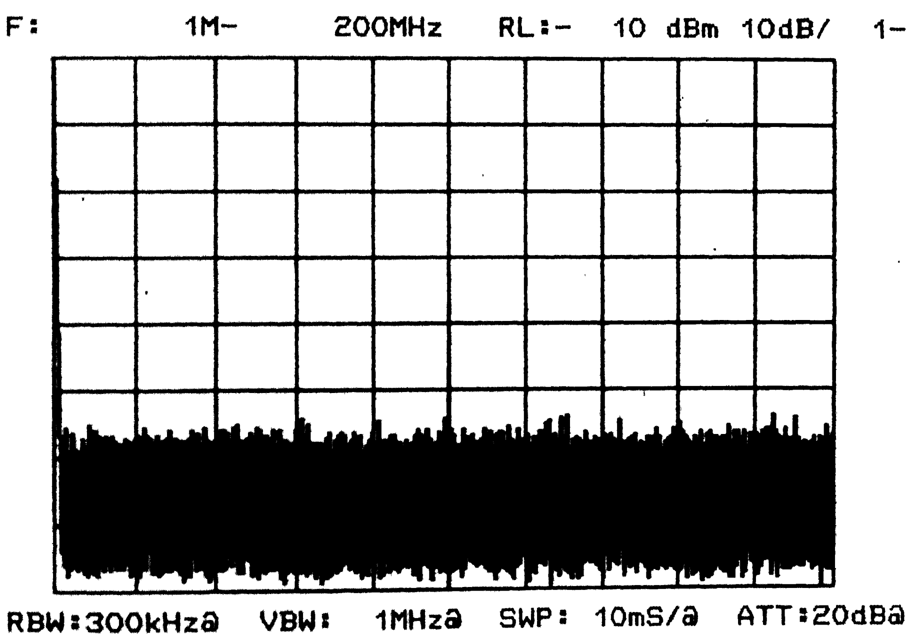


Fig. 4.53 : Frequency spectrum of noise due to setup without amplifier in circuit.

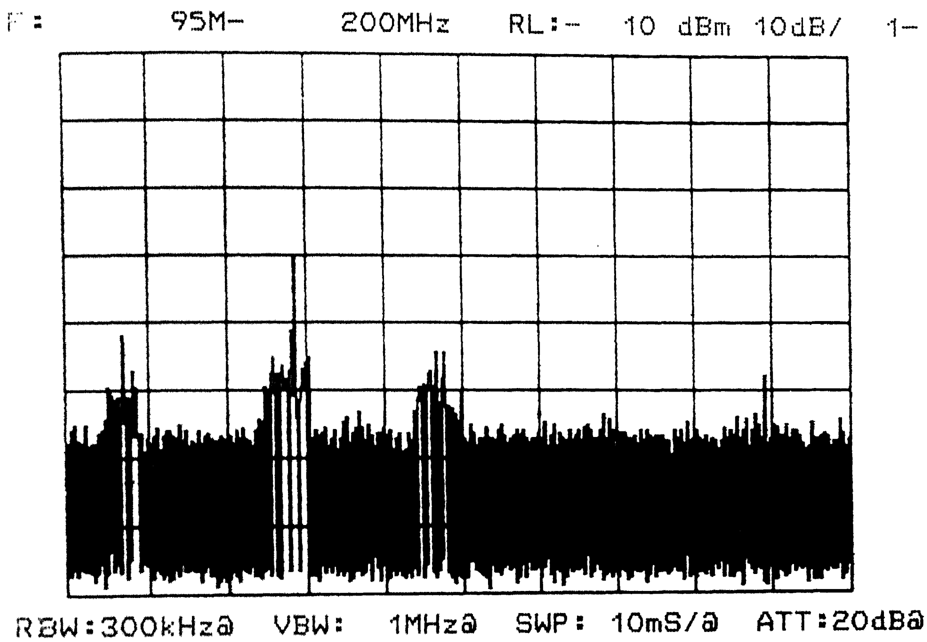


Fig. 4.54 : Frequency spectrum of EMI due to leader corona at 17 kV, without preamplifier in circuit.

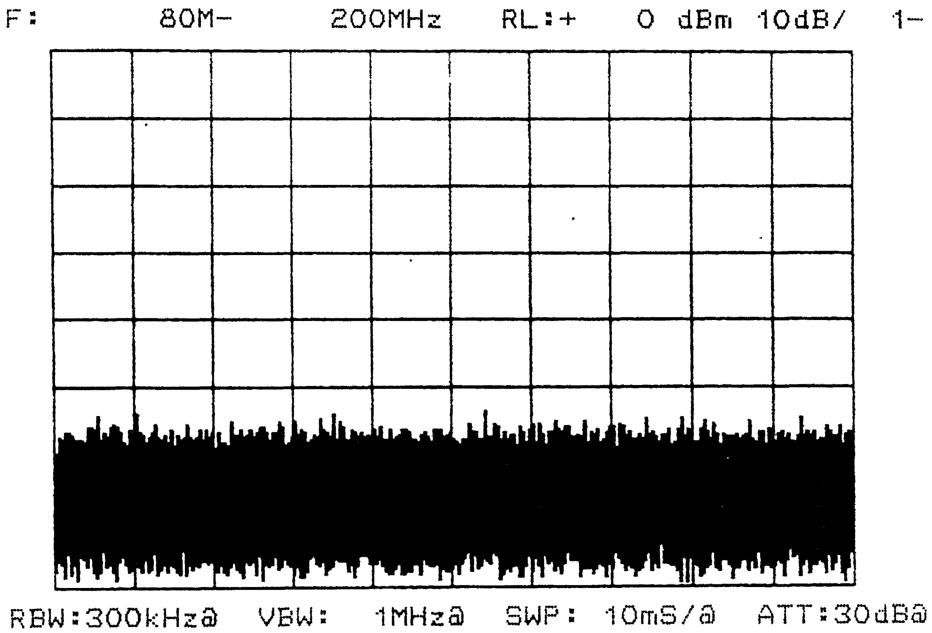


Fig. 4.55 : Frequency spectrum of noise due to setup with preamplifier in circuit.

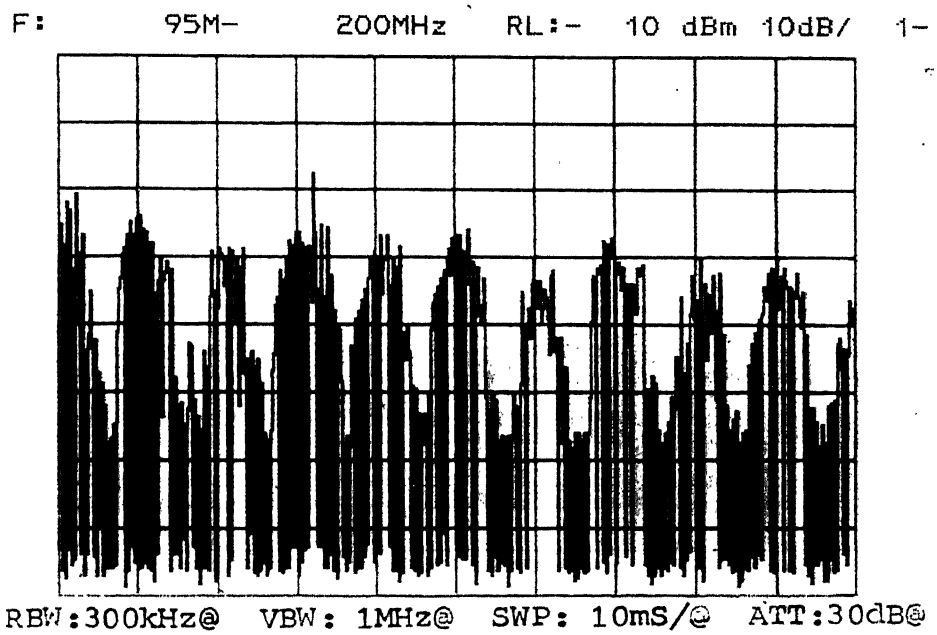


Fig. 4.56 : Frequency spectrum of EMI due to leader corona at 17 kV with preamplifier in circuit.

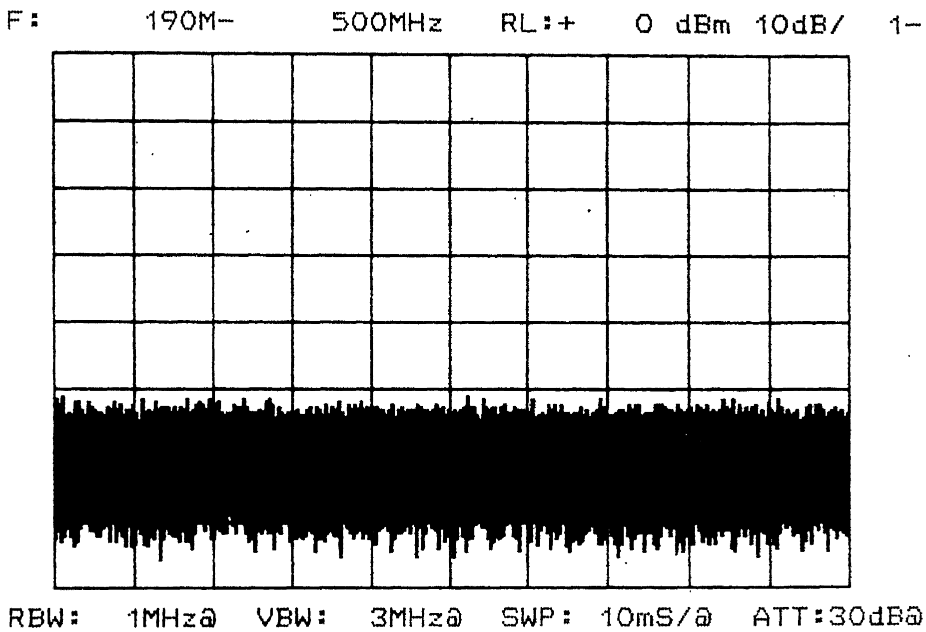


Fig. 4.57 : Frequency spectrum of noise due to setup with preamplifier in circuit.

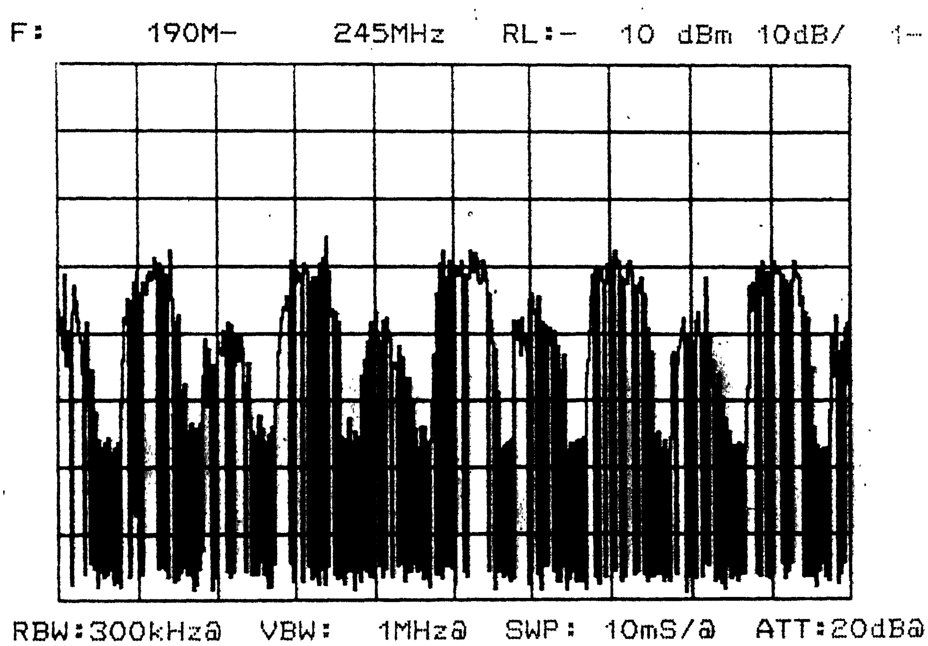


Fig. 4.58 : Frequency spectrum of EMI due to leader corona at 17 kV with preamplifier in circuit.

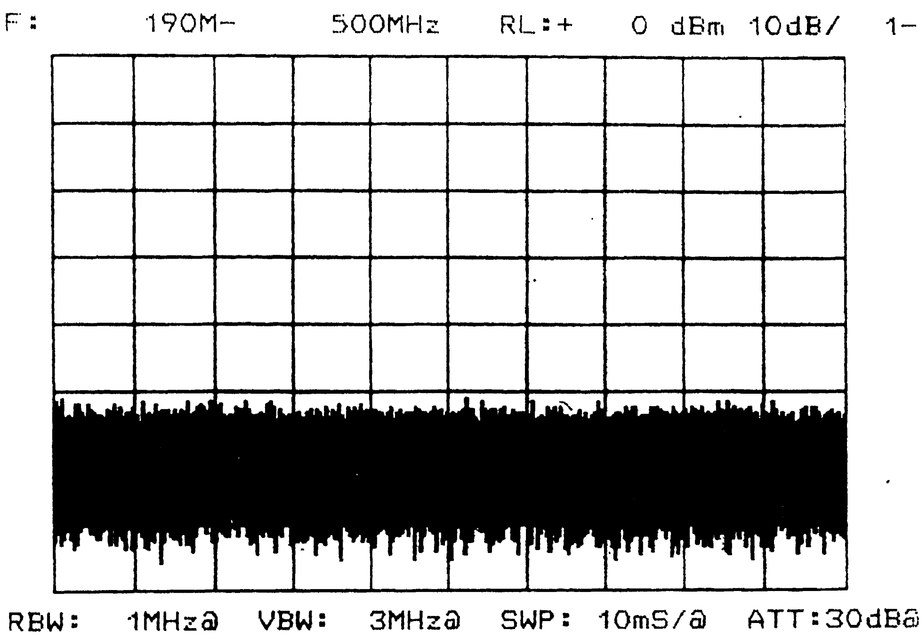


Fig. 4.59 : Frequency spectrum of noise due to setup with preamplifier in circuit.

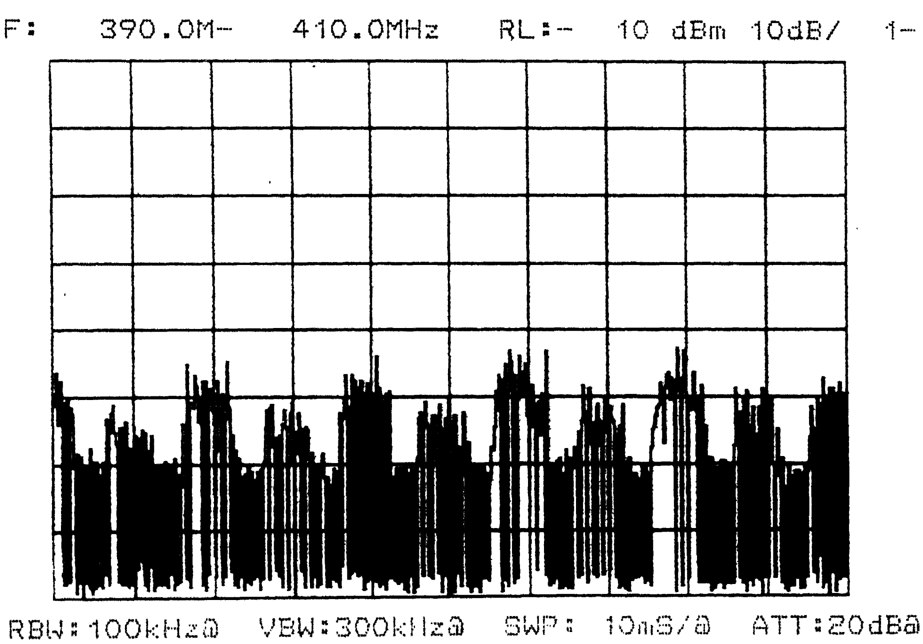


Fig. 4.60 : Frequency spectrum of leader corona at 17 kV, with preamplifier in circuit.

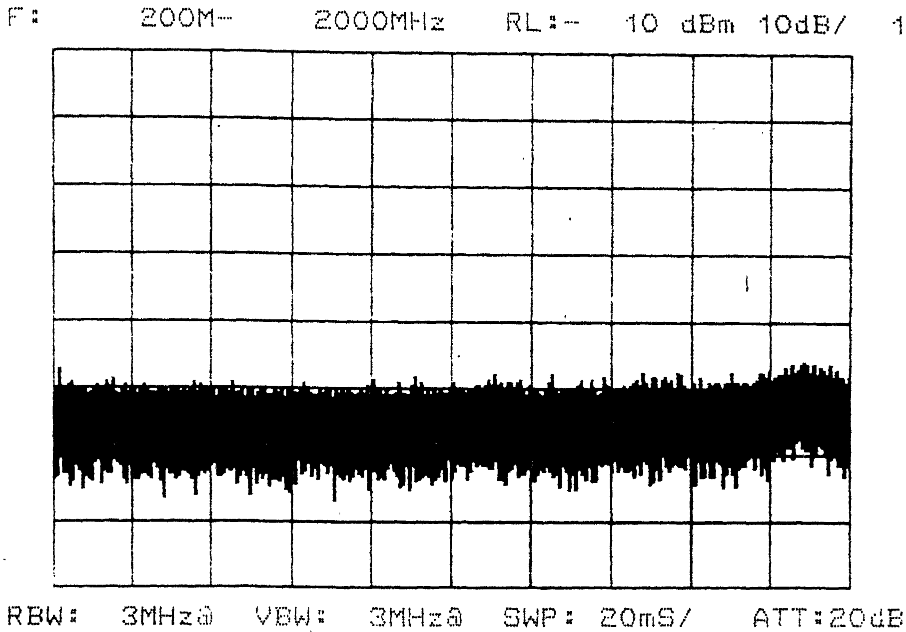


Fig. 4.61 : Frequency spectrum of noise due to setup with preamplifier in circuit.

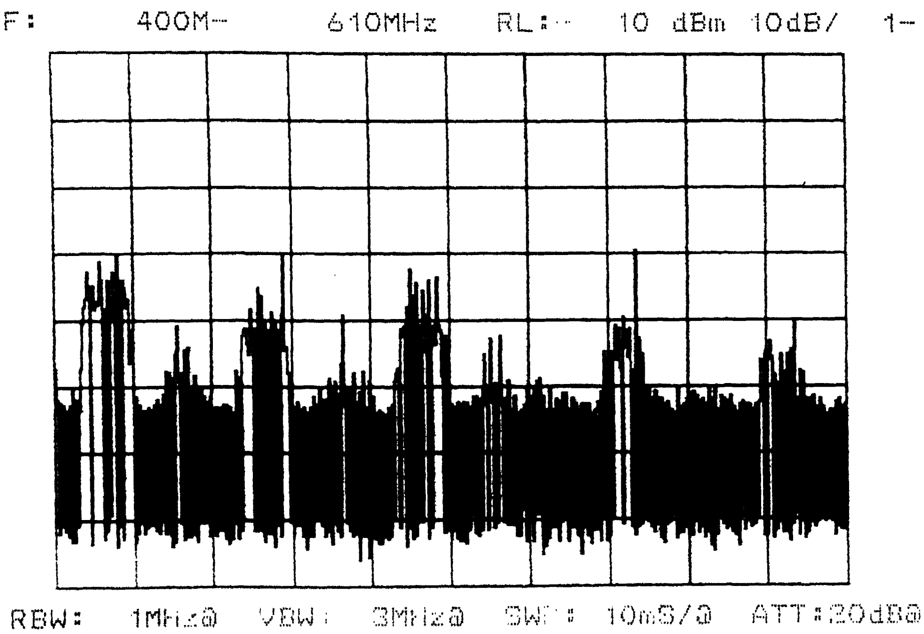


Fig. 4.62 : Frequency spectrum of EMI due to leader corona at 17 kV with preamplifier in circuit.

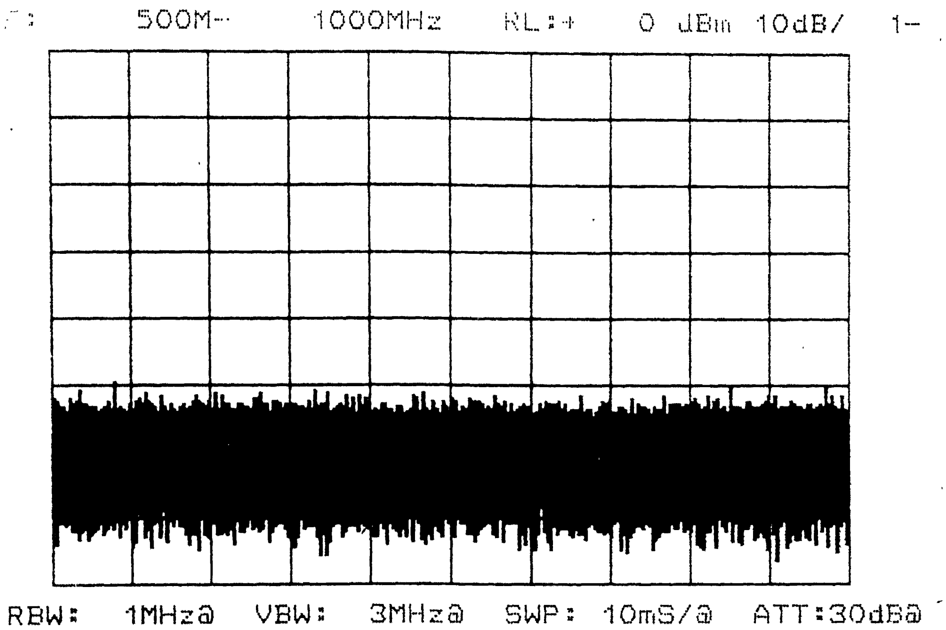


Fig. 4.63 : Frequency spectrum of noise due to setup with preamplifier in circuit.

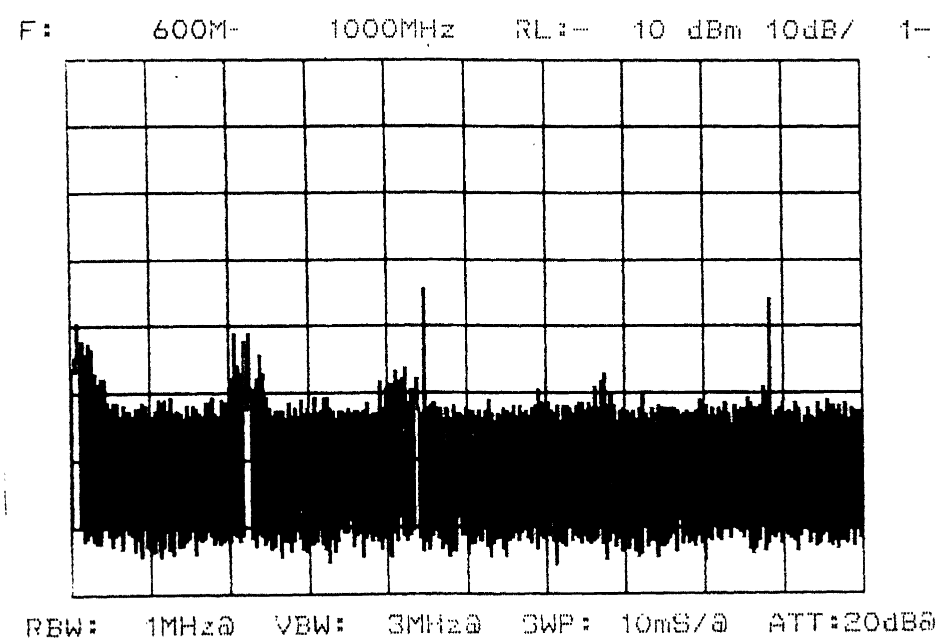


Fig. 4.64 : Frequency spectrum of EMI due to leader corona at 17 kV with preamplifier in circuit.

Fig. 4.65 : Shows effect of glow corona on TV picture

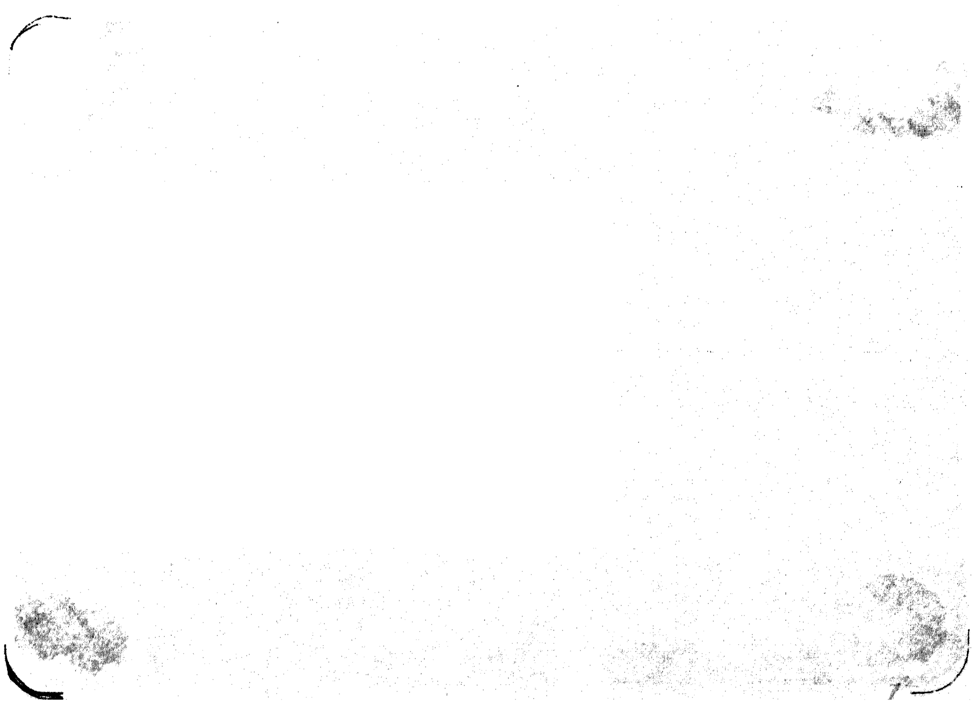


Fig. 4.66 : Shows effect of glow corona on TV picture

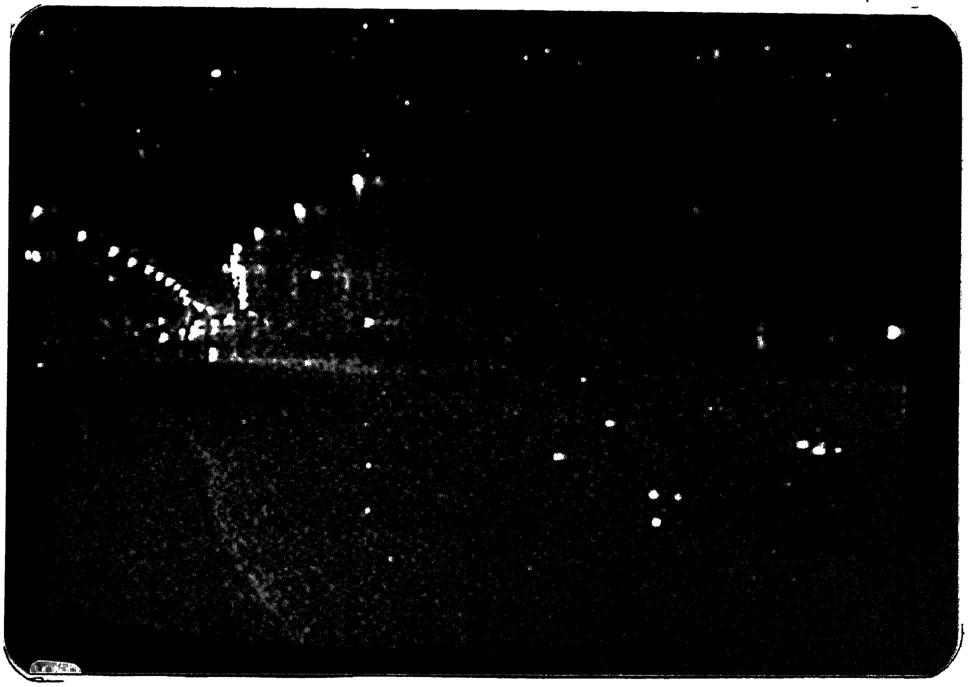


Fig. 4.67 : Shows effect of streamer corona on TV picture.

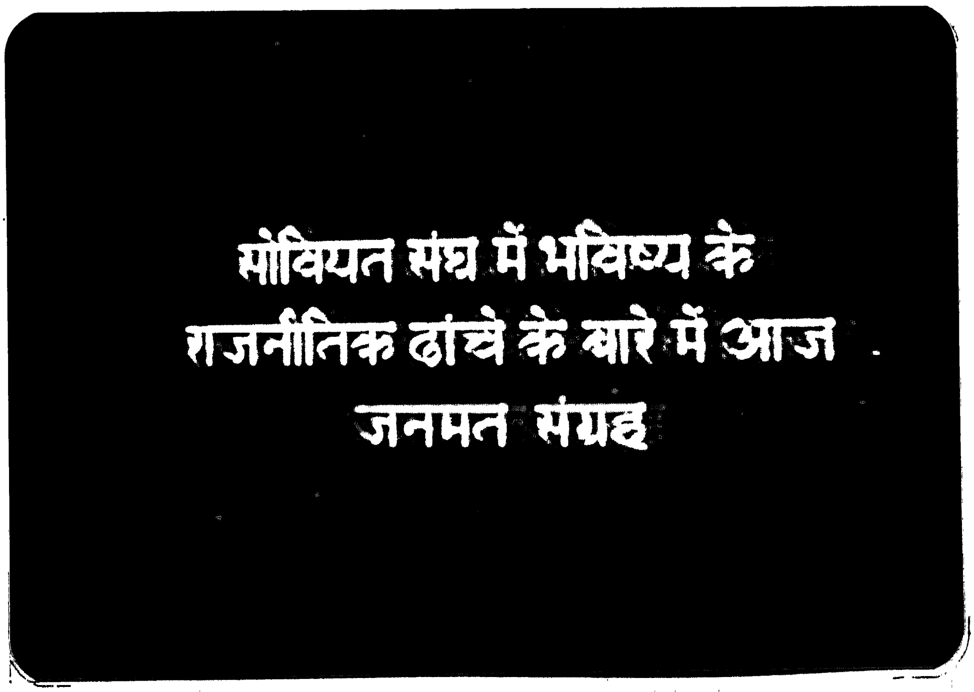


Fig. 4.68 : Shows effect of streamer corona on TV picture.

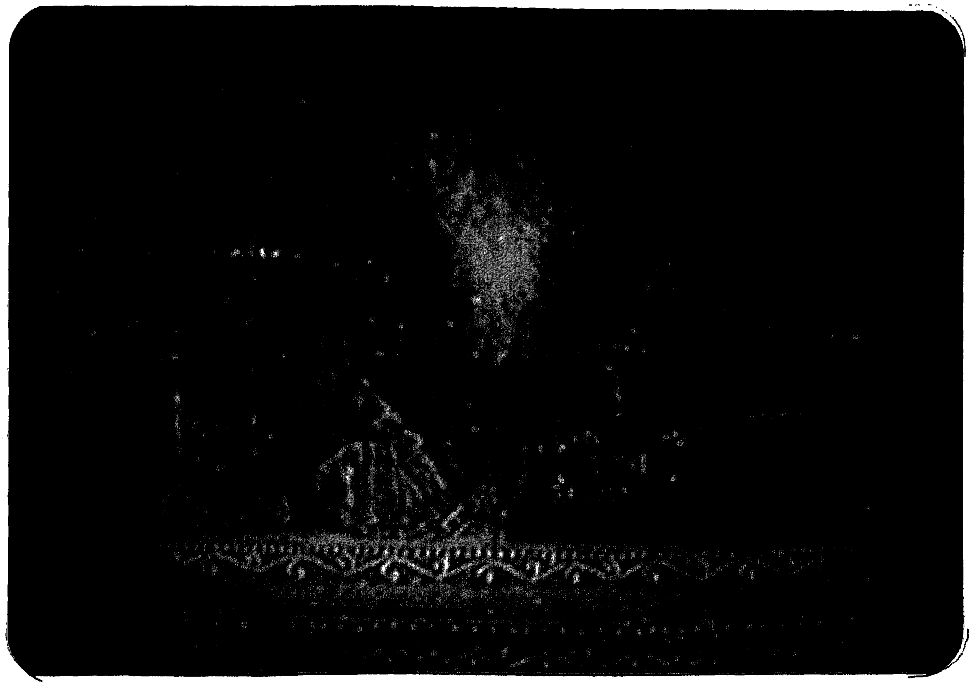


Fig. 4.69 : Shows effect of Leader corona on TV picture.

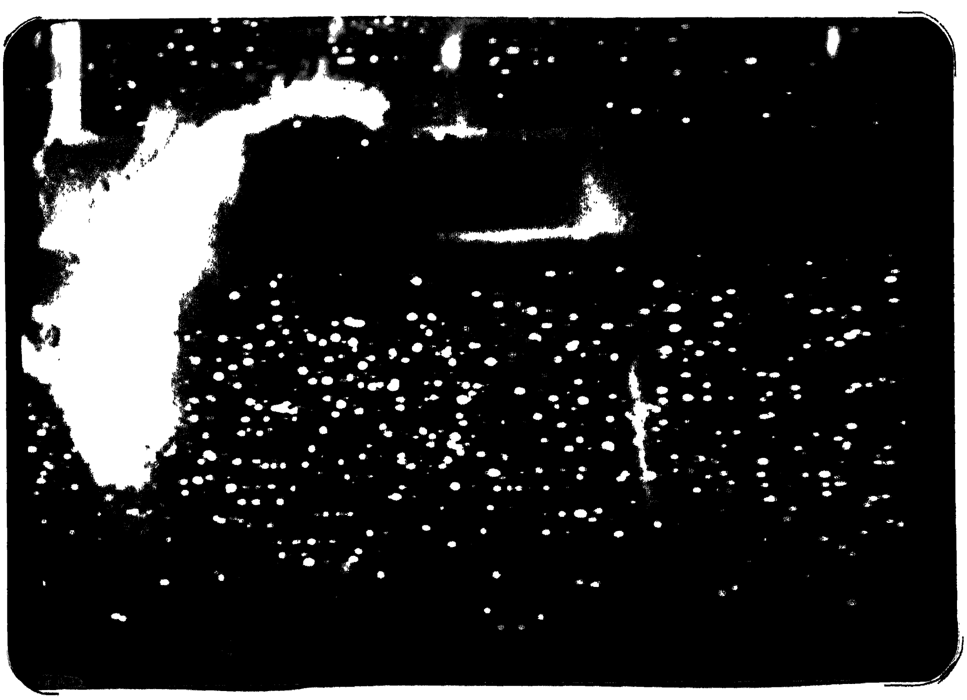


Fig. 4.70 : Shows effect of Leader corona on TV picture.

As there was no disturbance recorded on the TV picture due to *streamer corona* at 45 kV and no noise was detectable by the spectrum analyzer even with the amplifiers in the frequency range of 174 to 180.25 MHz shown in figure 4.40, it can be concluded that the response of spectrum analyzer is quite reliable.

Figure 4.69 and 4.70 show the effect of *leader corona* on TV picture. In this case beginning at fairly low voltage itself (17 kV), noise on TV picture appeared in the form of dense bright band of spots, besides spots being scattered all over the screen.

4.8 USE OF TRANSISTOR RADIO TO DEMONSTRATE THE EFFECT OF RI:

A transistor radio was used to hear the effect of various types of coronas on Medium and Shortwaves (9 to 12 MHz only). It was found that at 45 kV *glow* and *streamer corona* did not affect the medium and short wave frequencies, however , at higher voltages their effects of comparatively low intensity were detectable (audible). Leader corona interfered at MW (Medium wave) and SW (Short Wave) frequencies vigorously at fairly low voltage of the order of 17 kV. The performance of radio receiver in noisy atmosphere depends upon its selectivity sensitivity and fidelity. Therefore some receivers may get highly affected too much by corona noise and some comparatively less due to their high sensitivity, fidelity and selectivity.

CHAPTER 5

CONCLUSIONS

In this work an investigation of electromagnetic interference caused by different types of coronas in air was carried out with the help of spectrum analyzer and biconical and spiral log cone antenna. Following conclusions are drawn from the measured results:

1. The order of corona inception voltage for Tracking (Leader), *glow* and *streamer* for the given electrode systems was as follows:

Tracking	<	Glow	<	Streamer
(4 kV)		(10 kV)		(30 kV)

Corona inception voltages may vary slightly with different weather conditions and for different electrode setups.

2. Audible noise associated with *glow corona* was a hizz, due to *streamer corona* a fluttering and due to *leader corona* a cracking sound which could be heard.

3. Optical trace of coronas in dark was as follows:

<u>GLOW CORONA</u> : Just at the Anode is observed and this bluish *glow* remains confined to the anode only.

<u>STREAMER</u> <u>CORONA</u>: A less illuminated, shower like discharge at the anode was seen which varies in its extent in the gap contonuosly.

<u>LEADER</u> <u>CORONA</u>: Brightly illuminated circular and radial discharge channels are seen at the anode depending upon the shape ofthe electrode. In between the bright channels, less bright *streamer* are also present on the surface of the solid dielectric.

4. Level of radio noise increases with increase in applied voltage for all types of coronas irrespective of their inception levels.

5. Corona produces impulse discharge currents giving rise to electro magnetic waves at very wide frequency range causing interference.

6. Radio noise produced due to *glow*, *streamer* and *leader* coronas are of maximum intensity in the frequency ranges of 25 to 40 MHz, 38 to 43 MHz and 17 to 32 MHz respectively. Their intensity decreases beyond these frequency ranges. *Glow* and *streamer* corona were measured at 45 kV and Leader corona at 17 kV on the setup described.

7. Radio noise due to *glow* and *streamer* were not present beyond 460 and 160 MHz respectively and due to *leader corona* it was present even upto 1000 MHz.

8. The order of nuisence value caused by different coronas in the sense of their intensity and coverage of frequency range is:

Tracking (Leader) > Glow > Streamer

9. Pre-amplifier and power amplifier were used in cascade to increase the sensitivity of analyzer due to which noise figire increased upto 8.5 dB which brought down the sensitivity of analyzer to some extent. Therefore it is recommended that instead of cascaded amplifiers aingle amplifier of high gain and low noise figure should be used.

10. A spectrum analyzer is capable of making accurate measurement of spectral intensity of radio noise produced by experimental setup in a laboratory as well as from HV transmission lines.

11. A spectrum analyzer displays the magnitude of pulses of different repetition rate by superimposing them.

12. Radio noise produced due to corona cover a wide frequency spectrum which can be continually observed on the CRT of the analyzer . Photograph or printout of displayed spectrum can be taken whenever desired.

13. The noise due to *glow corona* appears on the TV Screen in the form of a band of small but comparatively less

bright spots.

14. The noise due to streamer corona appears on the TV screen in the form of scattered bright spots very few in number.

15. The noise due to leader corona appear on the screen in the form of a dense band of very bright spot besides a number of such spots scattered all over the screen.

16. Interference on MW and SW frequencies were measured by a small battery radio set covering frequencies from 520 to 1620 kHz and 9 to 12.5 MHz respectively at '3' metres away from the source. Radio interference to the receiver due to *glow* and *streamer* coronas werenegligible at lower voltages applied to the test object but were moderate at higher voltages (above 45 kV). It is interesting to note that the audible noise (AN) due to *glow* corona is audible at very low voltage itself (about 20 kV)and due to *streamer* corona at comparatively higher voltage (about 40 kV).

17. RI due to *leader* corona, when measured with the same radio set and at the same distance, was intensive in both the frequency ranges (MW & SW) at avery low voltage itself. The audible noise produced was very loud.

18. Having used the spectrum analyzer for the measurement of EMI due to PD it can be confidently said that spectrum analyzer is a very versatile instrument. It can be used

for monitoring the EMI [12] and hence for the detection of all the kinds of partial discharge. Calibration of the measuring circuit with the help of a standard generator, which generates pulses of desired charge (coulomb), may enable the measurement of intensity of partial discharge.

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APPENDIX A

LIST OF SYMBOLS

EMI	=	Electromagnetic interference
RI	=	Radio interference
TVI	=	TV interference
AN	=	Audible noise
RBW	=	Resolution bandwidth
VBW	=	Video bandwidth
SP	=	Frequency span / division
RL	=	Reference level
SWP	=	Sweep time / division
ATT	=	Input attenuation
m	=	Metre
ac	=	Alternating current
BW_i	=	Impulse bandwidth
f_L	=	Frequency width of main lobe of frequency spectrum
f_O	=	Signal generator frequency delivered to PIN modulator
f_r	=	Pulse repetitiom freqwuency = 1 / T
S	=	Spectral intensity of an impulse signal in r m s dB μV / m MHz
T	=	Time between two pulses
V_1	=	r m s voltage of pulse signal during " on " time
V_2	=	r m s voltage of single frequency line of impulse spectrum
V_p	=	Peak value of voltage transients (in r m s volts) at the output of a lossless filter having an impulse bandwidth (BW_i). caused by an impulse signal at the input
V_{p1}, V_{p2}	=	Peak value of voltage transients (in volts peak) at the input mixer created by a dc or RF pulse, respectively
Δf	=	1 / τ; difference between frequency f_o and frequency of adjacent zero of spectrum

τ	=	Half peak width of RF pulses; 1 / Δ f
τ_{eff}	=	Width of hypothetical rectangular pulse of the same height (V_1) and same area as the pulse
ACF	=	Antenna correction factor.
Vert	=	Vertical.
NF	=	Noise figure

APPENDIX B

MEASUREMENT OF IMPULSE BANDWIDTH, OPERATION OF SPECTRUM ANALYZER

And

CALCULATION OF NOISE FIGURE OF TWO CASCADED MODULES

Definition of Impulse Bandwidth:

Impulse signals of short duration having a frequency spectrum that far exceeds the bandwidth of a calibrated voltmeter and having a repetition frequency substantially less than the voltmeter bandwidth are termed broadband impulse signals. They are measured in terms of their spectral intensity in volts per megahertz or dB above one microvolt per megahertz.

Impulse signal cause transient responses in a voltmeter of limited bandwidth. The peak value of these responses is proportional to the spectral intensity of the impulse signal and to the bandwidth of voltmeter - the exact value of this voltmeter bandwidth has to be known in order measure the broadband impulse signals. It has been named the " Impulse bandwidth . Unlike the 3 - dB bandwidth, its value can not be found easily from CW response measurements because the transient behavior depends on the exact shape of the frequency response, on the design of the bandpass, or, if logarithmic amplifiers are used, on the gain shaping performance.

Impulse bandwidth (BW_i) is specified as the ratio of the peak value of the voltmeter transient (V_p) divided by the spectral intensity of the impulse signal (S) causing it :

$$BW_i = V_p / S \qquad (1)$$

Spectral intensity is specified in rms volts, so V_p must be measured in rms volts; that is, the absolute voltage peak of the transient must be divided by $\sqrt{2}$. This correction is not necessary in usual measurements since substitutions are carried out with CW signals, which are calibrated in rms values.

Measurement of Impulse Bandwidth by using PIN Modulator:

No spectrum analyzer shows the dc value of a pulse therefore modulate the pulse with the help of PIN modulator and RF signal generator so that the dc value of pulse will get shifted to frequency of discrete RF signal generator. Selection of RF signal frequency will depend upon the range of frequencies in which PIN modulator generates RF pulse.

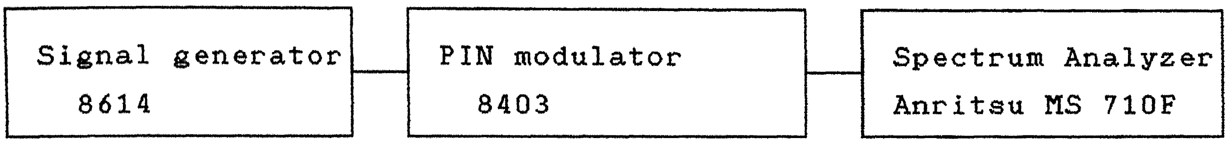

Figure B - 1

The PIN modulator is operated between its " on " and " off " state either by dc or by impulses. The amplitude of the signal generator CW signal leaving the PIN modulator during " on " condition is independent of PIN modulator pulse modulation frequency or pulse width. Figure B - 2 shows waveform of CW RF signal leaving the PIN modulator.

However, the PIN modulator, posses finite rise and fall times, so, in general, the signal at its output has the following shape given in figure B - 3.

The frequency spectrum of the impulse shown (see figure B-4) consists of discrete frequencies at f_o, $f_o + f_r$, $f_o - f_r$, $f_o + 2f_r$, $f_0 - 2f_r$, etc., or in general,

$$f_n = f_o \pm nf_r \qquad (2)$$

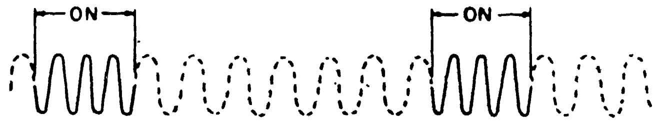

Fig. B-2

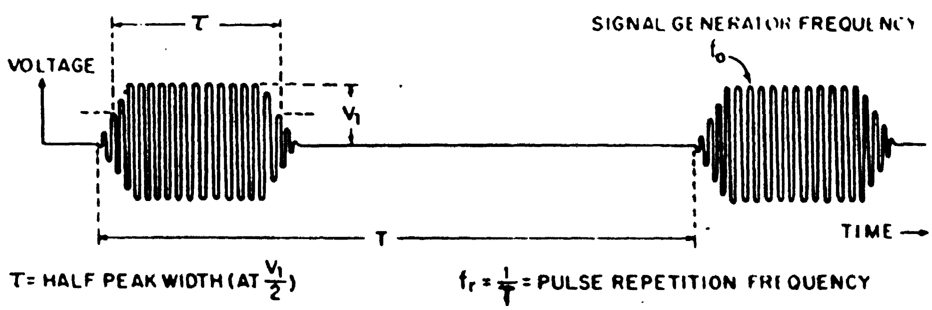

Figure B-3

The voltage of the frequency f_o is

$$V_{fo} = V_1 \tau_{eff} / T = V_1 . \tau_{eff} . f_r = V_1 . \frac{f_r}{\Delta f} . \frac{\tau_{eff}}{\tau} \qquad ....(3)$$

$\tau_{eff} = \tau$ for the 8403 PIN modulator for all practical purposes. This can be verified by measuring V_{fo} directly using a resolution bandwidth much narrower than the pulse repetition frequency f_r. Equation (3) then yields

$$\frac{\tau_{eff}}{\tau} = \frac{V_{fo}}{V_1} . \frac{\Delta f}{f_r} \qquad (4)$$

Use equation (4) to check the performance of PIN modulator before making the impulse bandwidth measurement. For a properly working instrument, Equation (4) will yield

$$\frac{\tau_{eff}}{\tau} = 1$$

The spectrum of impulse is shown in figure B -4. Its shape is determined by impulse width τ and the shape of the impulse in time domain presentation. The half- peak pulse width determines the zeros of the frequencies spectrum. Hence, measurement of frequency distance $2\Delta f$ between the two zeros adjacent to signal generator frequency f_o gives an accurate measure for impulse width (see figure B - 4); $\tau = 1/ \Delta f$.

For measurement of the impulse bandwidth, spectral intensity must be constant over the range of this bandwidth. Therefore, it is necessary to choose the impulse width narrow enough so that the flat portion extends well over the range of bandwidth to be measured. On the other hand, it is desirable to make the spectral intensity as high as possible by making the impulse width as wide

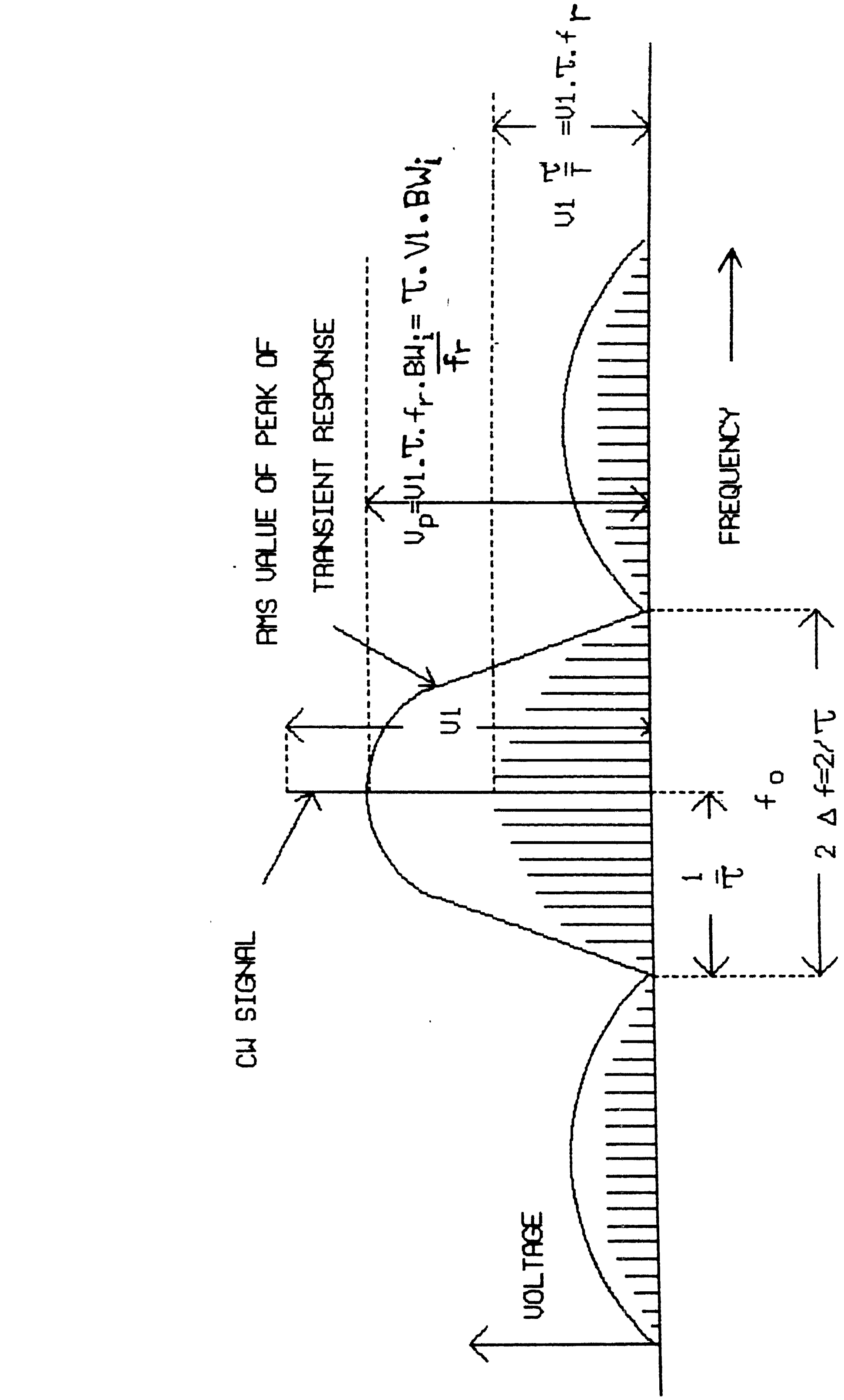
VOLTAGE
CW SIGNAL
RMS VALUE OF PEAK OF
TRANSIENT RESPONSE
V1
f o
1/τ
2 Δ f=2/τ
FREQUENCY
Vp=V1.τ.fr.BWi = τ.V1.BWi
fr
V1 τ/T =V1.τ.fr

Figure B-4

as possible.

In figure B - 4 the frequency spectrum is given for triangular pulse shape. For this, frequency $f_o + nf_r$ or $f_o - nf_r$ will have the following voltage voltage:

$$V_2 = V_{(fo_r \pm nf)} = V_1 . \tau . f_r . \left[\frac{\sin (\Pi . \tau . n \, f_r)}{\Pi . \tau . n . f_r} \right]^2 \quad (5$$

Normally, as frequencies outside twice the three 3 - dB bandwidth have very little effect on the peak voltage of the transient response of the voltmeter, it is sufficient to keep this portion flat. If we choose

$$1 / \tau = 10 \, BW_{3dB} \quad (6$$

It follows from equation (5) that a relative drop, a, in spectral line voltage between frequencies f_o and $f_o \pm (0.1 / \tau)$ will be:

$a_{\wedge}$ = 0.29 dB (This is flatness of response for a triangular impulse over twice 3 - dB bandwidth.)

...........(7)

$a_{\sqcap}$ = 0.14 dB (This is the flatness of response for a rectangular impulse over twice the 3 - dB bandwidth.)

...................(8)

<u>Volt meter Transient</u>:

The voltage peak of the voltmeter transient is the summation of the voltages of all the spectral lines within the bandwidth of the voltmeter. Due to the non - linear phase - versus frequency characterstics of bandpass filter around the stop - pass band boundaries, summation has to take phase (or delay) distortion into account. That is why it is difficult to determine the impulse bandwidth from measured frequency response alone. With a frequency spectrum extending well over the range of the bandwidth and consisting of discrete frequencies spaced at a distance of f_r apart and all having the same voltage V_2, the peak of the transient response of the voltmeter becomes

$$V_p = V_2 . m \tag{9}$$

where

$$m = \frac{BW_i}{f_r} = \text{number of spectral lines within the impulse bandwidth } BW_i. \tag{10}$$

Substituting equation (10), we get

$$V_p = V_2 . BW_i \, / \, f_r \tag{11}$$

and, with

$$V_2 = V_1 . \tau . \, f_r , \tag{12}$$

Equation (9) now becomes

$$V_p = V_1 . \tau . f_r . \frac{BW_i}{f_r} = V_1 . \tau . \, BW_i \tag{13}$$

Impulse Bandwidth is

$$BW_i = \frac{V_p}{V_1} . \frac{1}{\tau} ; \tag{14}$$

and spectral intensity is

$$S = \frac{V_2}{f_r} = \frac{V_1 . \tau . \, f_r}{f_r} = V_1 . \tau \tag{15}$$

(V_1 = rms volts of CW signal)

OPERATION OF SPECTRUM ANALYZER:

Maximum input which can be fed to spectrum analyzer was 30 dBm or 7.07 volts rms. It was taken for granted that field due to coronas produced in the lab can not be greater than or equal to 7 volt / m and hence noise signal due to various types of coronas was fed directly to spectrum analyzer. However to be on safer side, it is recommended to use sensitive RF voltmeter to first measure the input and then feed to the spectrum analyzer. One can also use RF power meter to measure the power of noise signal to be fed to the analyzer. But while using RF power meter one should be very careful that power sensor used along with power meter does not get damaged due to high input feeding above the specified input. After confirming that the level of input signal is less than the specified input level of analyzer , one should feed the signal to the analyzer otherwise attenuator at the input of the analyzer may get damaged. On increasing the attenuator at the input by 10 dB it was found that base line of frequency spectrum shifted upwards instead of top line of frequency spectrum going down . This was because the analyzer showed the absolute amplitude irrespective of input attenuation. This confirmed that the input amplifier was not over driven. An external attenuator in between the analyzer and amplifier would have been better in order to check the overloading of amplifier.

Care must be taken throughout the measurements to ensure that the measured signals or noise are from source, and not spurious responses due to analyzer overload. This may be checked by observing the displayed spectrum when the input attenuator is increased by 10 dB then measurements are from the source; if some displayed signals do not change in amplitude , it implies that there are spurious responses generated internally with in the analyzer. The settings of input attenuation, RBW (resolution Bandwidth), frequency span/division, sweep time etc . were recorded for each frequency band over which measurements were made. Printout of the frequency spectrum were recorded with the help of matrix printer in EPSON mode. Spectrum analyzer was provided with a parallel interface connector on its back to connect a printer.

<u>Formula to calculate Noise Figure of two cascaded modules of which individual gain and NF is given:</u>

Two amplifiers were used in cascade for EMI due to glow and streamer corona. One amplfier was pre-amplifier and another one was power amplifier. Pre-amplifier and power amplifier both had a gain and noise figure of 26, 22 dB and 8.5, 11 dB respectively.

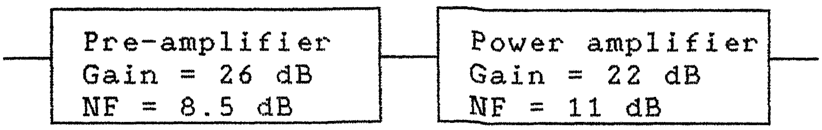

Figure B - 5

Formula to calculate noise figure of two cascaded modules:

$$F = F_1 + \frac{F_2 - 1}{G_1}$$

whereFisnoisefigureoftwocascademodulesinratio.

F_1 and F_2 are noise figure of pre-amplifier and power amplifier respecvtively in ratio.

G_1 gain of pre-amplifier in ratio

$F_1 = 7.08$, $F_2 = 12.59$ and $G_1 = 398.10$

$$F = 7.08 + \frac{12.59 - 1}{398.10} = 7.109 \text{ or } 8.51 \text{ dB}$$

$F = 8.51$ dB